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A SEAKEEPING PERFORMANCE AND AFFORDABILITY TRADEOFF STUDY FOR THE COAST GUARD OFFSHORE PATROL CUTTER

by

Paul T. Schmitz

June 2016

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A SEAKEEPING PERFORMANCE AND AFFORDABILITY TRADEOFF STUDY FOR THE COAST GUARD OFFSHORE PATROL CUTTER

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ABSTRACT

The United States Coast Guard Offshore Patrol Cutter program requires a method to analyze trades made between performance and affordability. Models of seakeeping performance were developed using linear seakeeping analysis, and a cost model was adopted from previous research. Both models were integrated into a decision support tool. Entering a notional Offshore Patrol Cutter design into the tool revealed that the program would likely perform well but could have a high cost risk. The decision support tool connects the two competing ideas of seakeeping performance and system affordability for program managers, while allowing different designs to be tested. Additional research into this topic should consider using more accurate seakeeping analysis techniques to create more accurate seakeeping performance prediction models.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADE	acquisition decision events
AVGCOST	average cost
BY	base year
CDF	cumulative density function
CER	cost estimating relationship
CG	Coast Guard
COI	composite operational index
DHS	Department of Homeland Security
DISP	displacement
ENGNUM	engine number
FOM	figure of merit
FRC	fast response cutter
FY	fiscal year
GAO	Government Accountability Office
KPP	key performance parameter
LBP	length between perpendiculars
LEN	length
LMR	living marine resources
NSC	national security cutter
OI	operational index
OPC	offshore patrol cutter
PDF	probability distribution function
PE	effective power
PM	program manager
PWCS	ports, waterways and coastal security
RAO	response amplitude operator
RMS	root mean square
SAR	search and rescue
USCG	United States Coast Guard
WMEC	medium endurance cutter

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EXECUTIVE SUMMARY

The United States Coast Guard is in the midst of modernizing its surface fleet. The Offshore Patrol Cutter (OPC) program will replace the legacy medium endurance cutter fleet. OPC will be largest acquisition program in Coast Guard history. A total of 25 cutters are planned for an average unit cost of $329 million FY16 (O'Rourke 2016, 4). Department of Homeland Security and Coast Guard studies have determined that there are high risks for several core missions including search and rescue, drug interdiction and living marine resources enforcement (Hutton and Caldwell 2012, 17). Functional analyses of these missions reveal that several key functions require good seakeeping qualities. Additionally, the Coast Guard has stated the biggest challenge for OPC is to be affordable (O'Rourke 2016, 14). These competing priorities have caused Congress to question the process through which performance tradeoffs are made to enhance affordability (O'Rourke 2016, 14). A process is proposed that connects performance and cost risks to give a program manager (PM) the information needed to make these trades early in an acquisition program.

A process is used to quantify performance and cost. Seakeeping performance is quantified using the Composite Operational Index. The operational index is a measure of the percentage of available vectors that do not violate the seakeeping criteria at a given sea state. Probability distribution functions are available that describe the likelihood that an operational area will experience any given sea state. Combining these two measures produces the composite operational index. This measure is the expected percentage of vectors available for any given operational area. Linear seakeeping theory is typically used to calculate this measure of effectiveness, but it has the disadvantage of requiring detailed hull geometry. A known parent hull was used to create multiple variants that each exhibited expected design ratios such as length to beam, beam to draft or length to draft. The seakeeping performance of these distinct hulls was used as the data to create seakeeping performance prediction models. Using linear regression and statistical software, composite operational index models were created for each operational area and programed into a decision support tool. Cost was quantified using a cost-estimating

model adopted from previous research. Quantifying cost and performance allows a program manager to test a notional design.

Risk and uncertainty are important aspects to consider. A point estimate is of limited value because the actual design will probably not exhibit those characteristics. Risk is the probability of an unwanted event occurring. Monte Carlo simulation was used to account for this uncertainty. Many different possible OPC designs were created and evaluated for cost and performance. With a large sample, risks were calculated. Performance risk is the probability that the performance of the OPC will be less than that of the legacy platform. Cost risk is the probability that the OPC will exceed the target cost. Presenting these risks in the decision support tool, a program manager has the information necessary to create a useful risk assessment.

A notional OPC design illustrated the utility of the decision support tool. Previous research compiled publicly available sources to create a realistic estimate of OPC design characteristics. These were entered into the decision support tool to create a risk assessment. The analysis revealed that the OPC would likely have a high chance of good performance but also a high risk of exceeding the budget. After identifying the risks, the program manager could adjust the design to trade some performance risk to decrease the cost risk. In this case, reducing the length and displacement of the OPC by 15% was considered. The reduced size OPC drastically limited cost risk for a modest increase in performance risk. This example illustrates that this tool can justify making design trades between performance and affordability.

Programming this methodology into a decision support tool delivers cost and performance estimation capabilities to a PM, while also incorporating aspects of uncertainty. This tool can be used earlier than other methods and for less cost. An example of the utility of the tool was presented using a notional OPC design. Balancing cost and performance is important because new platforms must be effective enough to perform their missions, but affordable enough to purchase all required systems. This tool will assist PMs in making the necessary tradeoffs to produce a low risk design and justifying the decisions made. Additional research should consider using more accurate seakeeping analysis techniques to produce a more accurate model.

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I. INTRODUCTION

The United States Coast Guard (USCG) has embarked on its largest acquisition program in service history. The Offshore Patrol Cutter (OPC) program plans on acquiring 25 cutters at an average cost of $310 million fiscal year (FY) 2012 or $329 million base year (BY) 2016 (O'Rourke 2016, 4). OPC will replace two classes of medium endurance cutters, 27 ships in total. The oldest of these cutters are over 50 years old, and the first OPC will only be procured in FY2018 (O'Rourke 2016, 4). OPC will contribute to the Coast Guard's threefold capabilities of maritime safety, security and stewardship by continuing the medium endurance cutter core missions of search and rescue, drug interdiction, and living marine resources enforcement (Commandant 2012, 8). An operational assessment of these critical missions revealed that all three missions share significant common functions. These functions require good seakeeping qualities. A Department of Homeland Security (DHS) study highlighted that seakeeping contributes to effective presence (Fritz, Gelhaus and Nordstrom 2011, 94). Seakeeping refers to the motions of a ship in a particular sea state. The OPC must perform well enough to reduce the risks to future missions but be affordable enough to purchase all the ships in the program of record.

Seakeeping performance is difficult to quantify at an early point in the acquisition program. Good seakeeping is defined by meeting a set of criteria, including the displacement of the motion in terms of distance and angle, the velocity of the motion and even the frequency of events such as propeller emergence or deck wetness. Linear seakeeping theory can produce an expected response for each criterion given an entering sea state. This approach is of limited usefulness early in the acquisition program because it requires detailed hull geometry and the vast quantity of data products makes analysis difficult. Early performance prediction is important because by the time a detailed design is created, a great deal of the total system cost is already committed, and it is much more difficult to make design changes (Blanchard and Fabrycky 2011, 48). To surmount this problem, seakeeping performance and sea state probabilities can be combined into one statistic, the Composite Operational Index. This statistic can form the basis for a seakeeping performance prediction model. Predicting performance is important because Congress has pointedly asked the Coast Guard about what process will be used to balance tradeoffs between performance and affordability (O'Rourke 2016, 14). This research proposes a process to quantify cost and performance risk, which allows decision makers to understand the impacts of future design changes.

This process is a tool meant to produce better decisions. The tool is intended for use by Coast Guard acquisition professionals involved in the Offshore Patrol Cutter program. A systems analysis of the requirements for a tool revealed that cost and performance risk must be quantified and presented, and that the process must be repeatable and capable of validation. Repeatability required that the program office be able to use the process without specialized tools or training. This requirement meant that the process was integrated into a tool to perform the analysis. Additionally, the tool shall be portable. This led to the decision to program the process into an Excel workbook because Excel is ubiquitous and present on most government computers. Validation meant proving that the analysis was correct and reflected reality. Ultimately, validation was beyond the scope of this research, though enough detail is provided so that others can replicate and validate the proposed process. The tool is the manifestation of the process.

Many different techniques were used to produce an analytic tool. Three primary considerations necessary to produce a tool were risk, modeling and uncertainty. Risk is the probability and severity of negative events occurring. Severity of consequences is the domain of decision makers because some element of risk will always be present and those leaders who are accountable for program success must be the ones that assess acceptable risk. For the OPC, the two risks being traded are the seakeeping performance and the cost. Seakeeping performance risk is the probability that the cutter will not be effective in the intended operational environments. Cost risk is the risk that the system will exceed the target unit cost. Some element of modeling is required because cost estimates must be calculated and a seakeeping performance prediction model is needed to circumvent some of the limitations of linear seakeeping theory. A conventional ship cost estimation model was adopted from a previous thesis. No seakeeping performance prediction model existed that did not require a high degree of detail not normally available early in an acquisition program. A model performing this function was created from data points obtained by performing a linear seakeeping analysis on a series of variant hulls descended from the hull of a legacy platform, the 270-foot Famous class cutter. These models provided an estimate of cost and seakeeping performance for a preliminary design. Uncertainty is an important consideration because the design characteristics are subject to change and there is a wide range of possible outcomes. Additionally, considering uncertainty allows an analysis to go from the dichotomy of positive or negative outcomes to determining the likelihood of these options. Adding uncertainty is done by implementing Monte Carlo simulation that creates possible designs by randomly selecting characteristics from user defined input ranges. Each consideration adds a different layer of calculations to the tool. Incorporating all the elements within an Excel file codifies the process for use by acquisition professionals.

The purpose of this tool is to allow a program manager (PM) to answer Congress' question of how performance and affordability trades are balanced. The main thrust is to produce a process and not necessarily to come to a conclusion about risks for the OPC program. One main reason is that accurate information about the potential designs is not available outside of the program office due to the ongoing competition among bidders for the OPC contract. Additionally, the proper assessment of risks should only lie with the primary decision maker. In this case, the Coast Guard's chief acquisition officer, the vice commandant, will be the one who will determine the point at which risks are too much. It is possible to apply conceptual characteristics to illustrate how the tool would work and a general prediction about some of the challenges the OPC program might face as it progresses toward a fielded system.

A notional design was used to illustrate the utility of the decision making tool. The notional design characteristics were obtained from previous research and input into the analytic tool. The results from the tool revealed that the notional OPC design would likely have a very small amount of performance risk, while having a significant amount of cost risk. This first analysis suggests that the proposed design might not be the best solution possible. An examination of relevant cost and performance factors suggests that reducing length and displacement could reduce the performance risk for a moderate increase in performance risk. Selectively reducing the design characteristics of the OPC greatly reduced the cost risk with a small rise in performance risk. This example not only illustrates how the tool could be used by a program office, but could help make better acquisition decisions.

Tying together seakeeping performance and cost provides key insights into how tradeoffs in a design can be made to achieve the dual objectives of a highly capable yet affordable platform. A methodology for measuring seakeeping performance and quantifying a design’s performance is proposed and described. A cost model was chosen and cost risks quantified. Both models were brought together within one tool along with techniques to account for uncertainty. This research revealed it was possible to create a tool to provide an answer to Congress about how performance tradeoffs can be made to achieve affordability.

II. BACKGROUND

The U.S. Coast Guard is in the midst of modernizing its fleet to replace ageing and obsolete assets across almost all mission areas. The need for this is that the current vessels are not as reliable and are increasingly expensive to maintain. According to the Government Accountability Office (GAO), Coast Guard vessel condition was rated as poor especially among the 270-foot Famous class and 210-foot-Reliance class, which only met operational availability targets for two out of seven years and three out of seven years, respectively from fiscal years 2005 to 2011 (Caldwell 2012, 11). In addition to being unavailable to complete missions, maintaining the legacy fleet is becoming increasingly costly. Famous class expenditures for scheduled and unscheduled depot maintenance exceeded the budgeted amount five of seven years from 2005 to 2011 with a maximum overrun of over double, while the Reliance class exceeded the budget four times over the same time period with a similar maximum overrun (Caldwell 2012, 59–60). Medium endurance cutters such as the Famous class and the Reliance class form the backbone of the Coast Guard’s fleet performing missions such as defense operations; search and rescue; living marine resources protection; ports, waterways and coastal security (PWCS); and illegal drug and migrant interdiction (Caldwell 2012, 5). To alleviate these problems, the Coast Guard is in the process of procuring the Offshore Patrol Cutter to replace the 13 Famous class cutters, 14 Reliance class cutters and two one-of-a-kind cutters (O’Rourke 2016, 4). This thesis will propose a key operational effectiveness problem facing the OPC and explore how the systems engineering process can help solve this problem.

A. OFFSHORE PATROL CUTTER PROGRAM

The OPC is anticipated to be an important component of the future Coast Guard surface fleet due to its numbers and key capabilities. It is intended to have an intermediate offshore presence capability greater than that provided by the Fast Response Cutter, but less than the National Security Cutter. In the words of Coast Guard Commandant Admiral Paul Zukunft:

> The OPC will be the backbone of Coast Guard offshore presence and the manifestation of our at-sea authorities. It is essential to stopping smugglers at sea, for interdicting undocumented migrants, rescuing mariners, enforcing fisheries laws, responding to disasters and protecting our ports. (United States Coast Guard Acquisition Directorate 2015, 1).

This United States Coast Guard Acquisition Directorate also describes the Offshore Patrol Cutter program as the Coast Guard's self-described highest investment priority. In addition to the critical capability gap that the OPC will fill, it will be the largest shipbuilding program in Coast Guard history. The current program of record calls for 25 cutters to be built for an average cost of $329 million starting in FY2018 for an overall cost of $10.5 billion (O'Rourke 2015, 4). Offshore Patrol Cutters will therefore be a major surface asset that operational commanders will be counting on to perform important missions in the future, and it is necessary that they be operationally effective systems.

In a fiscally constrained environment, major doubts exist about the future Coast Guard capability to perform several key missions including search and rescue, illegal drug interdiction and living marine resource protection. The Congressional Research Service, in a report on Coast Guard shipbuilding, has expressed concern that the quantities of cutters being requested for the future fleet will be too small and poses significant risks to key statutory missions (O'Rourke 2016, 17). Both SAR and illegal drug interdiction missions were assessed as being very high risk throughout the entire CG area of responsibility (AOR). Living marine resource protection likewise was assessed as high risk in the western operating area, CG districts 11, 13 and 14 as shown in Figure 1, and in the southeastern operating area, CG districts 7 and 8. However, the program of record presented only medium risk for the LMR mission in Alaska and the northeast, districts 17 and 1, respectively (O'Rourke 2016, 18). OPC will perform all three missions and the degree to which this risk is realized depends on the success of this program. OPC must manifest two disparate attributes: it must be affordable enough to build all 25 cutters in the program of record, if not more, and it must be more effective at performing these three missions than the legacy assets.

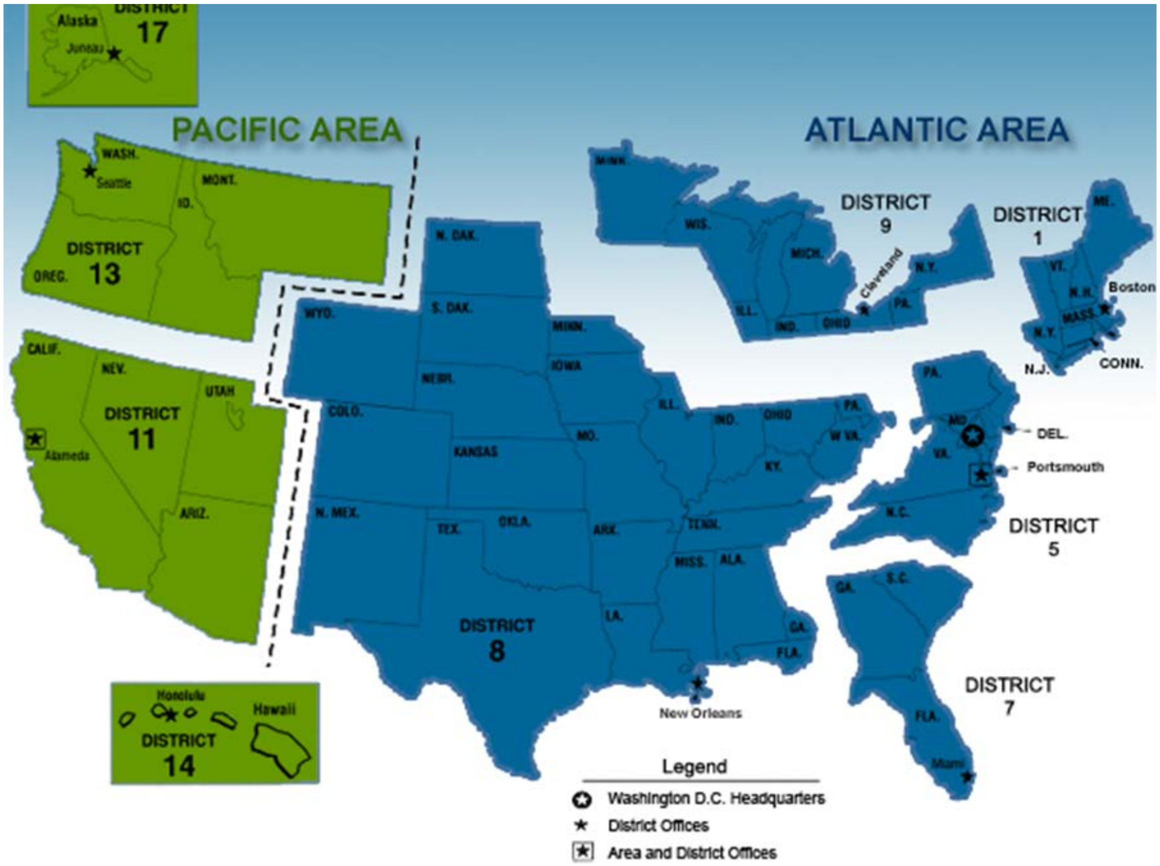

Figure 1. Coast Guard Districts and Areas of Responsibility. Source: United States Coast Guard (2014).

A closer examination of these three critical mission areas reveals that seakeeping performance is the effective need tying the three separate missions together. While affordability is certainly worthy of study, it is more useful to describe and present system performance tradeoffs to a decision maker in order to achieve affordability. The three critical mission areas described are seemingly unrelated having much different statutory backgrounds, policy objectives and typical geographic locations. However, the operational activities that are involved in performing these missions share common functions that require a certain level of seakeeping performance. For example, SAR typically occurs in heavy seas and foul weather and could require the launching and recovery of a helicopter. Here it is easy to understand how better seakeeping performance would allow a cutter to be more effective at SAR. The other missions are less direct.

Living marine resource protection operationally involves placing Coast Guard law enforcement officers on fishing vessels while they are operational and ensuring that they are complying with all applicable Federal laws. Decomposed, this mission requires the OPC to launch and recover small boats and transport boarding teams to the fishing vessels as shown highlighted in red in Figure 2. These activities require a minimum of vessel motion to be conducted safely. Commanding officers will often make binary “go-no go” decisions on performing boardings, based on their perception of the ship’s motions as influenced by the sea state. Reducing motion by making seakeeping improvements would increase the likelihood that any particular LMR boarding would take place. Considering that there are major fisheries in the Bering Sea and the North Atlantic where heavy sea states are more common, better seakeeping could have an impressive effect on mission performance in this area.

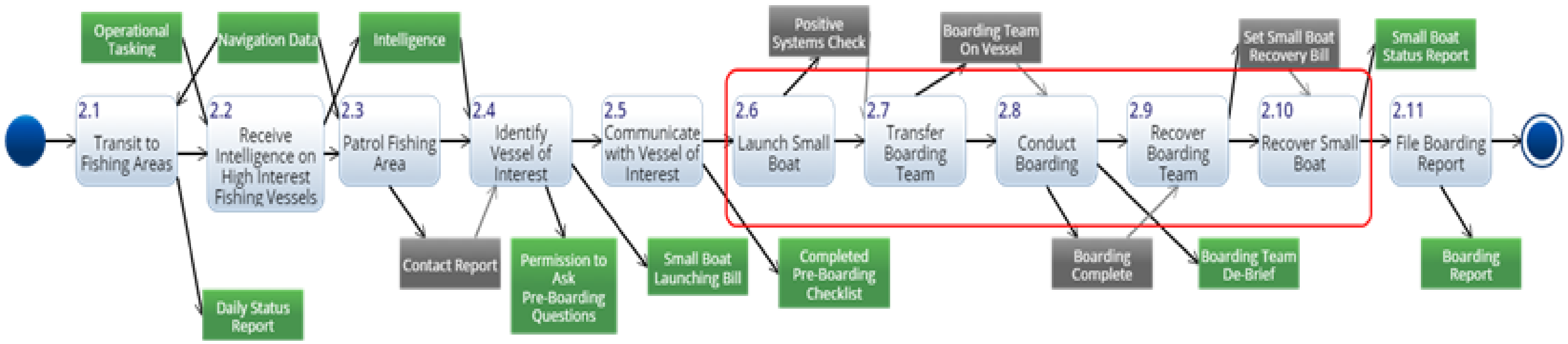

Figure 2. Activity Diagram for LMR Protection Mission, Red Outline Indicates Shared Operational Activities

In the same way, illegal drug interdiction requires a small boat to intercept drug-running vessels and board them. Figure 3 shows the flow of operational activities for the drug interdiction mission. Notice that while a separate mission, there are significant operational activity overlaps between the two. Operational activities can be traced to functions that describe, using verbs, the actions that a system is required to perform. Each function has a quality to its performance and the measurement of this quality is a requirement. The shared functionality means that across three critical missions for the OPC, seakeeping performance is paramount and should be a key performance parameter (KPP). In fact, the previous commandant, Admiral Robert Papp, in testimony to the House Appropriations Committee Subcommittee on Homeland Security on March 6, 2012, stated that the ability of the OPC to operate, meaning launch and recover, helicopters and small boats, in conditions up to and including sea state five was the most important aspect of performance. From this analysis of OPC missions, one can surmise that if one could quantify seakeeping performance, a significant amount of mission effectiveness would be explained.

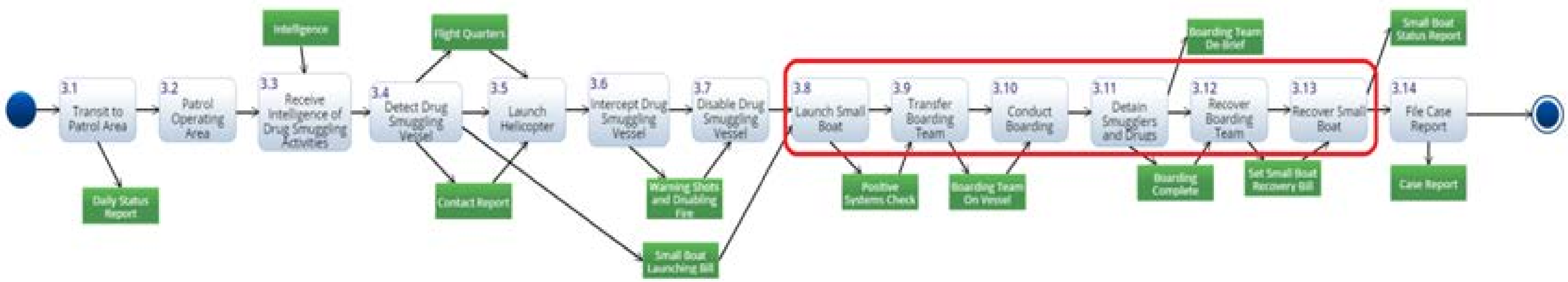

Figure 3. Activity Diagram for Illegal Drug Interdiction Mission, Red Outline Indicates Shared Operational Activities

If the Coast Guard were only interested in increasing seakeeping performance on the OPC, the analysis would be quite easy. However, affordability is also influential. Clearly, there is a tradeoff that is made between performance and affordability, and some process is used to make this decision. Unfortunately, Congress does not know this process and has repeatedly questioned how the Coast Guard evaluates trading performance to ensure affordability (O'Rourke 2016, 14). To ensure that the future Offshore Patrol Cutter can adequately perform the three critical missions of search and rescue, living marine resource protection, and illegal drug interdiction effectively, seakeeping performance must be considered during the analysis of alternatives and a method must be used to both understand and justify performance tradeoffs to improve affordability. This thesis will attempt to resolve this problem by proposing a method to quantify seakeeping performance and a process to perform seakeeping and affordability tradeoffs at an early point in the acquisition process.

B. APPLYING THE SYSTEMS ENGINEERING PROCESS

The systems engineering process is needed to create a process connecting performance and affordability that goes beyond simply answering the above question to become genuinely useful. To accomplish this, stakeholder needs were analyzed to determine where the capability gap exists. A functional analysis identified the actions the new method must perform and produced requirements for a new process. These requirements are traceable to user needs and verifiable. Ultimately, this will guide the research process to produce a useful new method for Coast Guard cutter acquisitions.

1. Stakeholders

The first step in the process is to identify the relevant stakeholders and their effective needs. Broadly speaking there are three major groups of stakeholders to the problem of tying performance and affordability together in the OPC program: the Coast Guard, DHS and Congress.

The Coast Guard wants an offshore patrol cutter that not only is capable of performing the same missions as the legacy WMEC platforms it is replacing, but is affordable enough to produce the amount of cutters needed to meet both current and future mission demands. While internal to the Coast Guard, there are many different actors representing the users and decision makers. The program manager is responsible for shepherding the offshore patrol cutter through the Coast Guard's major systems acquisition process (Assistant Commandant for Acquisition 2010, 1-10). The program manager will be the primary user of a new process and has three competing tasks to balance: requirements satisficing, data production and program justification. Data production is the easiest task to visualize and understand. The program office contains the information, plans and models of the OPC and is the entity that has the capability to produce the information needed such as modeling and simulation results or cost estimates. Any new methodology must fit into what the program office can produce without adding burdensome time and resource requirements. Related to data production is program justification. Ultimately, the PM is the primary face of the program and must interact with CG leadership, DHS and Congress to justify that the program is necessary, is producing new capabilities and funds are being spent responsibly (Assistant Commandant for Acquisition 2010, 1–12). These activities are the logical reason for why the data is being produced in the first place. Justification requires that all data products produced by a new methodology easily communicate the measure of performance and affordability and that it can be validated to provide the analytic products with credibility.

A PM's hardest task to perform is requirements satisficing. Satisficing occurs when an optimal solution cannot be determined or is very difficult to determine leading to a potentially sub-optimal decision being made provided that it satisfies basic requirements. In the OPC case, the PM has to deliver a system that meets both the seakeeping requirement and the affordability requirement. Are these requirements in competition and how much leverage does the PM have to modify the requirements? To be useful, any new method must drive straight to this problem and clearly delineate how the solution space is constrained by the requirements and where potential solutions lie within the space. As the primary user of this new process, the program office's needs must be accounted for in the final product.

Outside of the Coast Guard, the Department of Homeland Security maintains acquisition decision event authority for the OPC program and has a significant amount of influence on the design. With the overall power either to approve the program to proceed to the next development phase or to cancel it, the acquisition decision event authority within DHS has two main objectives at the acquisition decision event reviews: to ensure that the proposed system design will deliver the required capabilities within the department and that the cost of the system will not exceed the proportional benefit its capability brings to the department (Under Secretary for Management 2015, 2). The Coast Guard is only one organization within DHS and some missions might have more importance at the departmental level than others. For a new process to support this level of scrutiny, it must differentiate between system performance suitability across the whole spectrum of missions. An earlier example showed the similarity between operational activities across missions, but a key difference in missions is the environment in which the mission is performed. Fisheries' enforcement in the Bering Sea is more likely to be undertaken in a higher sea state than drug interdiction in the Caribbean Sea is. DHS could choose to accept a greater level of risk in one mission area in order to achieve affordability and a process exploring performance and affordability trades must allow for this. Homeland Security's effective need for a new process is to be able to measure differences in system performance across different missions or through different operational areas. Finally, Congress is an important stakeholder. Congress provides legislative oversight above both the Coast Guard and the Department of Homeland Security. Additionally, Congress controls the funding necessary to build OPCs. Congress needs some validated process that ensures trades made to achieve affordability do not seriously degrade performance. Both Congress and DHS need to make informed decisions about how allocate scarce resources using trustworthy data.

2. Capabilities

In summation, the stakeholder's capability gap is some method to understand and justify tradeoffs between performance and affordability at an early stage in the design process. Because the OPC program is a major acquisition program, the framework for which major decisions are made is defined by the Coast *Guard's Major Systems Acquisition Manual* as illustrated in Figure 4.

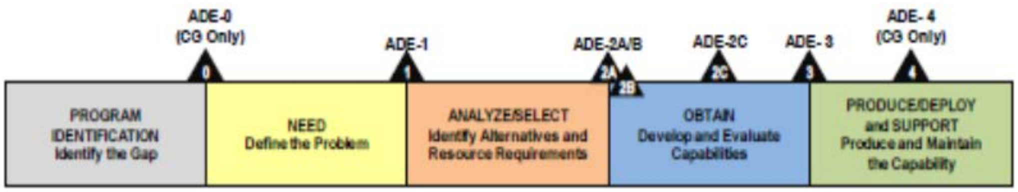

Figure 4. Coast Guard Major Systems Acquisition Life Cycle Framework. Source: Assistant Commandant for Acquisitions (2010).

While decisions are made every day by engineers and the program manager, major decisions are formally made at Acquisition Decision Events (ADE). The purpose of the review at each ADE is formally to receive authorization to proceed to the next acquisition phase. Within each review there will be a review of progress, summary of relevant decisions needed and an acquisition decision memorandum will be produced (Assistant Commandant for Acquisition 2010, 2–5). Understanding this process is important because the information identified as the capability gap will be consumed at this review and will feed into the decision making structure at this critical point. The logical place within the framework for the new methodology is within the Analyze/Select phase. This phase proposes and evaluates alternatives within an Analysis of Alternatives to choose a preferred solution that can be developed into a feasible capability within the Obtain phase (Assistant Commandant for Acquisition 2010, 2–14). The new process could take basic information about the hull characteristics of different alternatives and estimate the operational effectiveness enabling an analysis of alternatives. With an understanding of the capability gap and its location within the greater Coast Guard acquisition process a functional analysis will determine the requirements for the proposed solution.

3. Functions and Requirements

A functional analysis will reveal the actions necessary for a system to fulfill the given capability gap. Functions are the actions that a system must perform to achieve a needed capability. Each function is one specific action, though they can be decomposed into lower level functions. Three distinct functions are required to achieve the observed capability gap. First, the solution will be replicable. This means that the program office must be able to verify the solution by replicating the results following the same procedure. Information is more trustworthy and valuable if multiple parties can arrive at the same conclusions when following a standard process. The second function necessary is to evaluate a cost performance ratio. Implicit in this function are the related sub-functions of quantifying seakeeping performance and quantifying affordability. Seakeeping performance is dependent on both hull characteristics and operational environment. In calm seas, a ship does not need to possess excellent seakeeping characteristics. Affordability is a difficult attribute to assess because there is so much variance. A BMW might be affordable for one person, while another might struggle to make payments on a Kia. To alleviate this problem, only costs will be calculated and the determination of affordability will be left to the decision maker to adjudicate. This function will quantify the tradeoff between seakeeping performance and cost.

The final function is to justify the tradeoffs that are being proposed. Admittedly, nothing can be completely justified to all people, but a defendable case can be built by using common benchmarks and validating the proposed solution. Common benchmarks include using standard tasks to describe the critical missions being analyzed and standard measures of effectiveness to quantify performance. Using these common terms leaves no ambiguity in what the terms mean and established doctrine defines what is acceptable. Validation occurs when the predictions made about cost and performance are measured against existing systems to assess if the process output adequately represents reality. These functions describe what the solution must do and can be refined into the following four requirements.

1. The new process shall be repeatable by the Coast Guard program office.
2. The new process shall quantify performance risk.
3. The new process shall quantify cost risk.
4. The new process shall be capable of validation.

In addition, the functions can be used to allocate components. Components are the specific things that perform the functions. These have either to be created or compiled from other sources. There are four primary components that are required: a seakeeping model, a sea state model, a cost model and a cost benefit diagram. The seakeeping model has to be developed and will take basic hull characteristics and use them to predict the operational index. This index is the percentage of vectors that do not violate established seakeeping criteria at a given sea state. A distribution function can be created by evaluating the operational index across all sea states. Sea state models exist for all major oceans and are the probability density functions that a given part of an ocean is at a certain sea state. There are many cost models for ships available and one will be incorporated within the process. All this data will be distilled within a cost benefit diagram that will illustrate the solution space to a decision maker and will illustrate the performance tradeoffs made to reduce costs by modifying hull characteristics. These requirements and component description describe the proposed process and how it will quantify seakeeping performance to justify trades made to ensure affordability.

C. SEAKEEPING

Seakeeping has been briefly mentioned, but it is a very large area that deserves greater focus. Seakeeping at is most fundamental level is the response of a ship to being displaced by ocean waves. While this may seem trivial and unimportant, it touches on many aspects of operating a ship at sea. Poor seakeeping can damage structures, render personnel incapable through motion sickness or affect operations such as flight evolutions. As described earlier, within the context of Coast Guard operations the ability to predict seakeeping performance at an early stage would be incredibly beneficial. To make predictions, seakeeping analyses must be performed on known hulls to create information that can be used in a predictive model. One must understand how this information is obtained in order to make reasonable predictions. The salient points covered will be basic wave theory, quantifying ship motions and various criteria used to assess the sea kindliness of a hull that all lead to the calculation of an operational index to quantify this attribute.

Anyone with even a passing familiarity with the ocean will agree that its most salient characteristic is its waves. Most ocean waves are the result of energy that has been transferred to the ocean via winds blowing across the water (Zubaly 2011, 299). Zubaly suggests that the first place to start when considering a mathematical model for wave behavior is with a sinusoidal function as shown in Equation 1. ζ is the height of the wave above the water surface while ζ_a is the wave amplitude. *K* is the wave number that is described in Equation 2 and is a function of the wave length. *X* and *t* are the horizontal position and time, respectively, while *V* is the wave velocity (Zubaly 2011, 301).

$$\zeta = \zeta_a \cos k(x - V_w t) \tag{1}$$

$$k = \frac{2\pi}{L_w} \tag{2}$$

The generalized wave equation can describe any sinusoidal wave as long as it conforms to some basic assumptions. The first assumption is that all waves are long crested. This means that all waves are infinitely long. The other assumption is that all waves are regular, meaning that they are identical. (Zubaly 2011, 300) Of course, these assumptions become troublesome when one considers ocean waves are by their very nature unpredictable. In addition, waves generally do not exhibit a perfectly sinusoidal shape; instead, most waves exhibit a shape like that in Figure 5. However, these problems can be surmounted by conducting a spectral analysis of the wave.

Figure 5. Experimental Record of an Irregular Ocean Wave.
Source: Lewis (1989).

Using spectral analysis techniques, real waves can be broken into their component sinusoidal waves. Any wave form can be described as the summation of component waves each with the form of Equation 3 as shown in Lewis.

$$\zeta_i(t) = \bar{\zeta}_i \cos(-\omega_i t + \varepsilon_i) \tag{3}$$

In this equation, $\bar{\zeta}_i$ is the amplitude of the component wave, ω_i the wave frequency and ε_i the random phase angle. The ocean wave would be the summation of all of these component waves. Any periodic function such as a wave can be described in both as a function of time and frequency. This relationship is shown in Equation 4 where the variance of all wave components with the frequency ω_i in the time domain corresponds to a very small slice of the frequency band.

$$\left\langle \zeta_i(t)^2 \right\rangle \equiv S(\omega_i)\delta\omega \tag{4}$$

$$Unit\ Energy = \frac{1}{2}\rho g \bar{\zeta}^2 \tag{5}$$

Amplitude as a function of time is important because energy is primarily a function of wave amplitude as shown in Equation 5 where ρg is the water density and can be assumed to be a constant. Taken together this means that a specific amount of a wave's energy resides at each specific frequency. To calculate the variance spectrum, one would take the Fourier transform of the variance function. The resulting function is in Figure 6 along with the component waves that compose the original wave. Many wave spectra have been developed and can be used to model realistic ocean waves. This technique is very useful because it allows one to model realistic waves using component sinusoids.

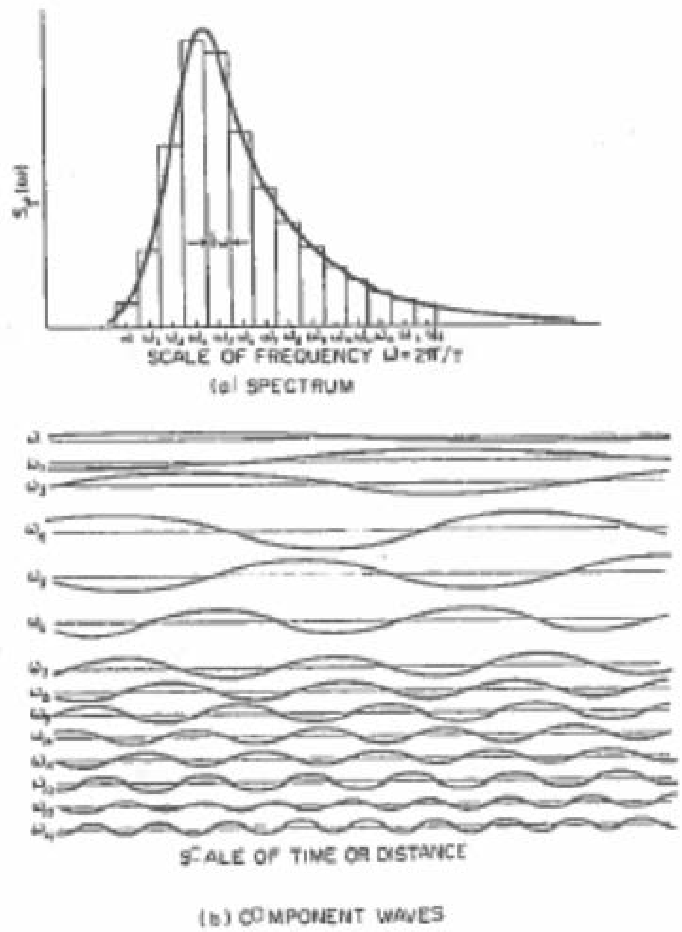

Figure 6. Graphical Presentation of a Variance Spectrum Top Being Decomposed into Component Waves. Source: Lewis (1989).

Spectral analysis is an effective technique when considering seakeeping analysis because of the principle of linear superposition. Linear superposition states that a ship response is the sum of the responses to individual component waves (Zubaly 2011, 321). Taking a wave spectra one can make component regular waves. Those regular waves can be used to displace a hull and the response of the hull can be measured. The summation of these measurements would be equivalent to the motion that would be experienced by an irregular or real ocean wave. There are several assumptions that must be adhered to that allow one to use linear superposition. First, this principle assumes that the ship is moving at a uniform speed and at a steady heading. Second, this assumes that the ocean considered must be a statistically stationary and a Normal random process. (Zubaly 2011, 322) These two assumptions mean that this analysis is valid for short term responses only. Effects such as weather patterns and maneuvering preclude this sort of process being useful for longer term predictions. To predict the seakeeping characteristics of a hull these assumptions will not pose a problem. Finally, the response amplitudes must be linearly proportional to wave amplitude. This means that for weather experienced in normal operations, this assumption is valid, but it ceases to hold as the vessel experiences severe weather. For the purposes of creating a seakeeping performance model, this level of analysis will be suitable.

From the principle of linear superposition, a method for determining the response of a ship to a seaway can be developed. To enable this, the motions of the ship must be considered. A ship has six different modes of motion that it can experience which are illustrated in Figure 7: heave, sway, surge, yaw, pitch and roll. Of these, the three that are of most interest are heave, pitch and roll because the other motions are of such small magnitude to be insignificant. The linear assumption made previously was that the amplitude of the response is proportional to the amplitude of the wave. This relationship yields the response amplitude operator as shown in Equations 6, 7 and 8.

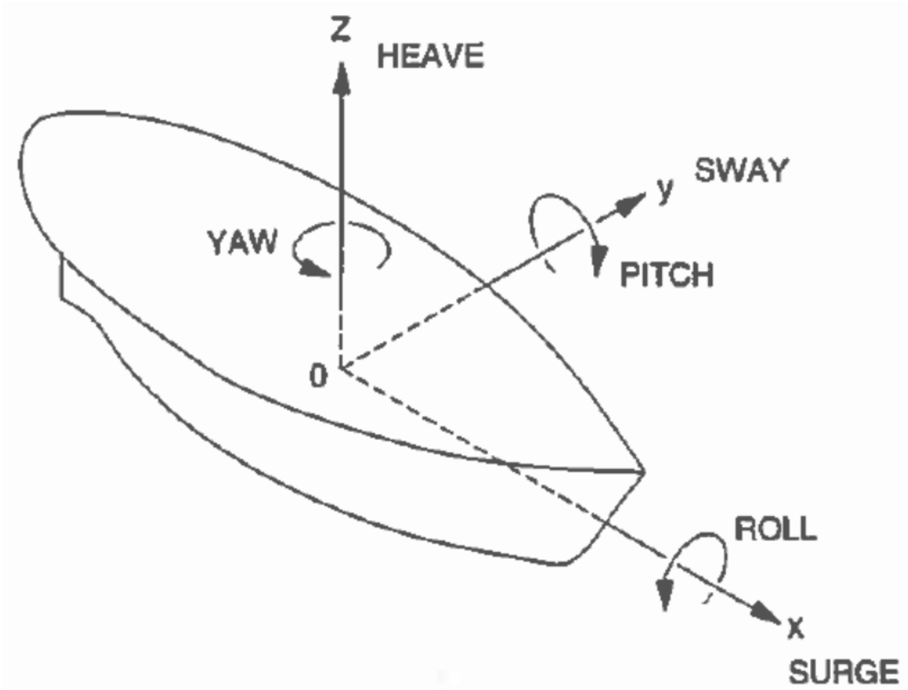

Figure 7. Six Degrees of Ship Motions from Applied Naval Architecture
Source: Zubaly (2011).

$$\textit{Heave}\ \text{RAO} = \Upsilon_{Z\zeta} = \frac{z_a}{\zeta_a} \tag{6}$$

$$\textit{Pitch}\ \text{RAO} = \Upsilon_{\theta\zeta} = \frac{\theta_a}{\zeta_a} \tag{7}$$

$$\textit{Roll}\ \text{RAO} = \Upsilon_{\varphi\zeta} = \frac{\varphi_a}{\zeta_a} \tag{8}$$

The RAO is important because it can be calculated using the equations of motion or through model based testing. A plotted RAO is included in Figure 8. An RAO is a function of wave frequency and as such, it needs manipulation before it can reveal useful information. The RAO simply describes the ship responses across the whole range of wave frequencies, but of interest is the response to the particular irregular wave that was developed earlier. The response spectrum is the product of the wave spectrum and the RAO as shown in Equation 9 and plotted in Figure 8. In this case, the response spectrum for heave is calculated.

$$S_z(\omega_i) = S_\zeta(\omega_i) \times (\Upsilon_{Z\zeta})_i^2 \tag{9}$$

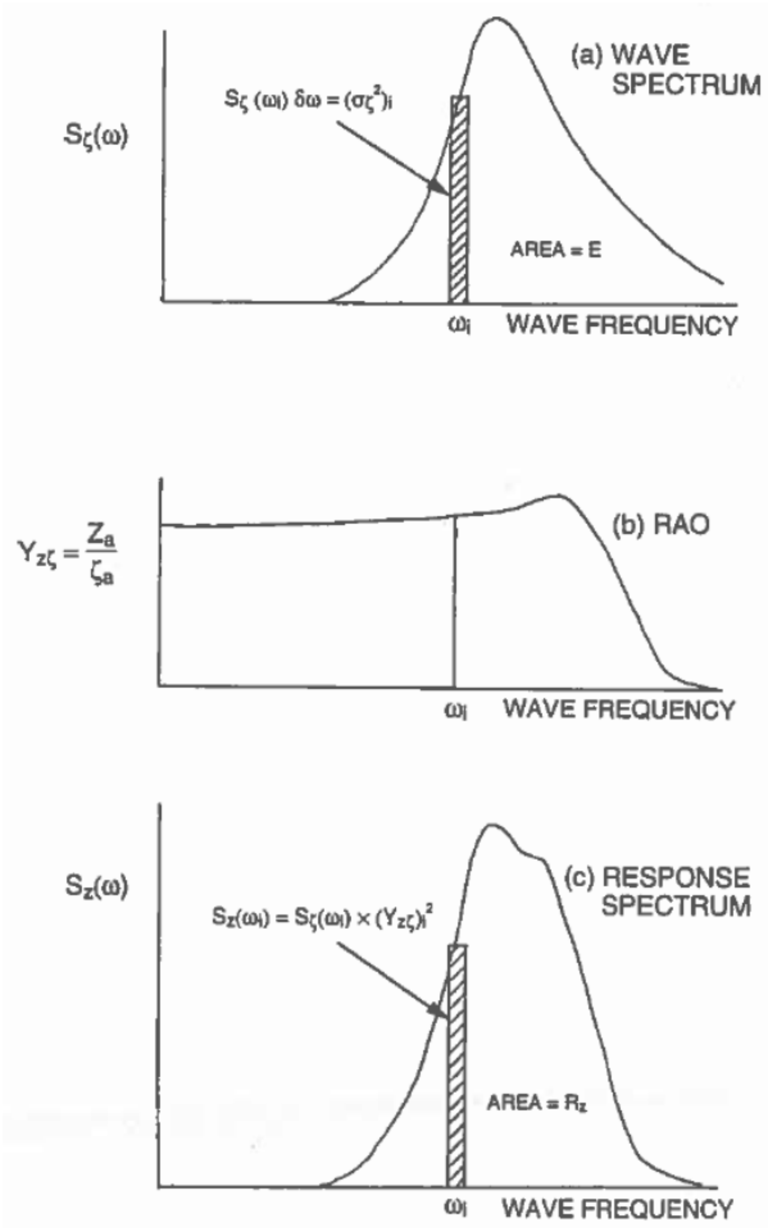

Figure 8. Graphical Process for Developing the Response Spectrum. Source: Zubaly (2011).

With the response spectrum, the actual magnitude can be predicted. In the same way that the wave spectrum was the sum of all the contributions from component waves, the motions resulting from the component waves form the response spectrum. The component waves do not exist in any discernable sense in reality, but the response is the totality of all the contributions. Mathematically integrating the response spectrum across all frequencies will yield the total mean square variance of the amplitude as illustrated in Equation 10.

$$R_Z = \int_0^\infty S_Z(\omega) d\omega \tag{1}$$

Variances are typically reported as root mean squares necessitating that the square root is taken. Additionally, there is a multiplier for the variance to calculate the specific response requested. Ocean waves were assumed to be irregular; therefore, the variance should be interpreted as that magnitude of motion or less with a certain probability. For most seakeeping calculations, the significant response amplitude is used which corresponds to a 95% confidence level. (Lewis 1989, 91) To calculate significant response amplitude, one would use Equation 11 where R is the previously calculated response. This amplitude will be used to assess if the vessel meets pre-established seakeeping criteria.

$$\text{Significant Response Amplitude} = 2.0\sqrt{R} \tag{11}$$

There are many reasons why seakeeping is important in ship design and should be considered. These reasons fall into three broad categories mission effectiveness, the crew, and the ship itself. (Lewis 1989, 142) Seakeeping affects mission effectiveness because excessive motions can preclude certain missions such as flight operations and small boat operations from occurring. If these tasks do not occur, mission success can be jeopardized. Additionally, the seakeeping performance has a large effect on the crew. Large motions tend to degrade crew performance. Excessive motions will induce motion sickness, which can incapacitate crew members, while even motions that do not reach this level can result in extreme crew discomfort also affecting performance. Safety is also a factor because unsecured items can be displaced by ship motions causing injuries. Finally, ship motions can affect the ship itself. Excessive forces impacting the hull can damage the ship structure requiring expensive repairs or a reduced service life. Large motions can also affect the ship propulsion plant through propeller emergence or racing events. Propeller racing can cause damage to the propulsion plant and can reduce the vessel's fuel efficiency. These varied reasons all have their own specific criteria for what is permissible and a response might be acceptable for one task and not acceptable for another. The criteria that will be used are detailed in Table 1 for the three relevant operational activities being considered. Significant response amplitudes calculated previously are only applicable for one location at one speed and relative heading. To evaluate the seakeeping performance of a design properly, the criteria must be applied across all relevant speeds and headings. While there are many criteria that have been defined for each operational activity, the decision of whether an operational activity is possible is binary. The activity is either possible or not, one is typically not interested in how much the criteria is violated by or exceeded. For each point in the solution space, there will be a pass or fail adjudication for each operational activity. The design would be deemed fully operational if all three operational activities can be performed at that particular speed and heading. Quantifying this leads to the operational index which describes seakeeping performance for a given sea state.

Table 1. Seakeeping Performance Criteria. Adapted from Lewis (1989) and Thomas III, Bachman, Lee and Applebee (1996).

Criteria	Transit Operations	Helicopter Flight Operations	Small Boat Operations
RMS, Roll Angle, deg.	8.0	4.0	8.0
RMS, Pitch Angle, deg.	3.0	2.5	2.5
RMS Vertical Acceleration, g	0.4	N/A	0.2
RMS Lateral Acceleration, g	0.2	N/A	N/A
RMS, Vertical Displacement, m	N/A	1.26	N/A
Motion Sickness Incidence	20% in 2 hours	N/A	N/A
Slam Acceleration, g.	0.2	0.2	N/A
Slam Frequency	20/ hour	0.03	N/A
Deck Wetness Frequency	30 /hour	30 /hour	N/A
RMS Relative Vertical Velocity, m/s	N/A	1.83	N/A

Operational index is a measure of performance quantifying the suitability of the seakeeping performance for a given sea state. The operation index is the ratio of incidents, a discrete speed and heading, which do not permit all operational activities over all possible incidents. Operational indices across all sea states will be compiled into a single function describing a particular design’s seakeeping performance. The criteria used define what is required to perform the operational activities that are required to perform the three critical missions of search and rescue, illegal drug interdiction, and living marine resources protection. The lengthy introduction to linear seakeeping describes what is necessary to calculate the motions expected for a particular hull and the operational index connects the two to adjudicate the suitability of a hull for the expected mission sets. This process will be used to develop a seakeeping performance model to predict the operational index from basic hull characteristics. Linear seakeeping theory forms the foundation of this research. Ultimately, the assumptions made to use this tool, linear superposition, increase the uncertainty of the results as the sea state increases. While this is undesirable, there is so much uncertainty early in the design process that even with an ideal method to calculate seakeeping, the results would still not reflect the delivered system due to uncertainty outside the researcher's control. This should not distract one from seeking information to enable a decision. Linear seakeeping theory will provide a good enough description of seakeeping performance to give a decision maker insight into tradeoffs made between performance and affordability.

III. METHODOLOGY

The salient problem facing the decision maker tasked with making tradeoffs with the Offshore Patrol Cutter is that there has to be some way to tie together cost and performance. Cost estimating for ships is well understood and there are many options available to predict the cost of a future ship. Performance prediction is complicated by several factors. First, seakeeping properties are heavily dependent on the hull geometry leaving a performance assessment until much later in the design process. Additionally, the performance is dependent on the operational area because each ocean has particular oceanographic and climatological factors that influence the wave periods and amplitudes that the ship is likely to experience leading to different degrees of effectiveness in different environments. To resolve these two complications and meet the research requirements previously delineated, a seakeeping performance prediction model is required along with a cost estimating model. Combined they will produce a cost and performance risk estimate to allow a decision maker to make trades in the ship characteristics to reduce cost and performance uncertainty to satisfactory levels.

A. RISK

Cost and performance risk must be adequately defined before attempting to quantify them. Cost risk is the easiest to deal with. This type of risk is defined as the uncertainty that the OPC will exceed the target average unit cost of $329 million. A cost estimating model will provide a probability distribution of costs and the cost risk would be the probability that the cost will be greater than the target cost. Seakeeping performance risk is much more difficult to define. This task is difficult because of the way that seakeeping is accessed. Typically seakeeping is assessed by creating a polar plot for a given sea state of the operational envelope that does not violate the different criteria. This can be quantified by calculating an operational index (OI) which is the ratio of vectors that do not violate the criteria over the total available vectors in the state space. A limitation of this idea is that while a larger OI is obviously better, a low OI does not necessarily mean that the system is not effective at that point. Another limitation is that as previously mentioned, the OI is only good for one specific sea state. Surmounting these two limitations will allow for a proper definition of seakeeping performance risk.

Of the two key limitations to using the operational index as a measure of effectiveness, the variability of sea states is the easiest to overcome. To do this the operational index must be transformed from being a function of sea state to a function of a particular area. Ocean observation has created a great deal of data regarding waves experienced in different parts of the world. The four key areas being considered are the North Pacific, North Atlantic, Caribbean Sea and Bering Sea. These were chosen because of the overarching mission performance risks described in the previous chapter. Resources such as the Atlas of Naval Operational Environments and the Principles of Naval Architecture have developed probability distribution functions (PDF) of the likelihood that a particular ocean is in a certain sea state at any given time. While this would certainly not be the best way to predict the sea state an hour from now or tomorrow, it should be satisfactory for a decision maker weighing different characteristics and trying to predict sea states a decade from now. A similar function can be created by calculating the OI for all possible sea states. Multiplying the functions and integrating through all sea states will mathematically account for the performance of a hull in a given sea state and the likelihood that it will experience said sea state. This single number will be the Composite Operational Index (COI) for each given operational area. The COI is defined as the expected percentage of the performance envelope available to an operator at any given time for a specific operational area. This can be further consolidated into a figure of merit that is a weighted COI across all expected operational areas. The weights would be assigned by the decision maker according to the importance of operations in a given locale and the amount of time the OPC will be operating in that environment. For the purpose of this research, it is assumed that the four areas considered are all equally weighted, though the decision support tool that was developed allows this to be changed if desired. The figure of merit is one number that describes the expected amount of the performance envelope open at any given time. While this does make it easier to talk about the relative merits of different designs, it still does not fully answer the question of how much seakeeping performance is good enough.

This loaded question can only be partially answered. Operational testing and comparative analysis of different vessels would be required to definitively calculate a COI that could be designed to. Even this might create an overdesigned and expensive ship. Ultimately, this question can only be answered adequately by operators and it is outside of this researcher's competence to propose a suitable requirement. What is known is the performance of the legacy platform. Acquisition professionals would agree that new systems should generally deliver at least the same level of performance if not more than the legacy platforms they replace. The performance risk will be the uncertainty that a specific design will have a figure of merit less than that of the legacy Famous-class cutter that it is replacing. Quantifying cost and performance risk will give definite reference points to a decision maker when considering tradeoffs in performance to increase affordability.

To truly quantify the cost and performance risk, uncertainty must be considered. At an early stage in the acquisition process, there is significant uncertainty in nearly every aspect of the program. Design parameters, program quantities and funding streams are all subject to change. In such circumstances, point estimates are inappropriate because the entering arguments that created the estimate will probably change before the program is complete and the estimate can be truly be assessed. A better approach is to accept inputs as a range of values. This is done using Monte Carlo simulation. Monte Carlo simulation randomly creates iterations of possible designs and presents the range of cost and performance. From this, a probability can be determined that will best encapsulate the risks facing the decision maker. Before this can be completed, a seakeeping performance prediction model must be developed.

B. SEAKEEPING PERFORMANCE PREDICTION MODEL

Predicting the seakeeping performance of future ship designs requires three separate tasks. First, several hulls must be created to provide data points to create a usable model. Second, the seakeeping performance of each hull must be assessed using linear seakeeping theory. Finally, this data can be used to create a model incorporating one or several of the predictors. Completing these tasks will create a usable model providing insights into the sea kindliness of a ship without the need to create a detailed hull design.

1. Hull Creation

A key task necessary to implement a model of seakeeping performance is to create data points based on observed results from various hulls. Implicit in this is the need to identify pertinent design factors that could be used in a potential model and create hulls exhibiting these design factors to farm the data needed for a model. Dimensional ratios will be used as factors in a seakeeping model because they are generic, can be applied to any ship design, and are widely used in Cost Estimating Relationships (CER) so they interface well with many decision support systems in use. A methodology for creating new hulls by selectively varying design ratios using Microsoft Excel is also presented. The primary outcome will be a set of hulls that will provide performance data points necessary to create a seakeeping performance model.

The first step in this process is to select factors that can be varied to produce the necessary hulls. Every ship has four main dimensions length, beam, depth and draft. Length is how long the ship is between two fixed points. For the purposes of this thesis, length between perpendiculars (LBP) will be used. Beam is the maximum width of the vessel at the waterline. The depth of a vessel is the height from the molded baseline to top of the main deck at the midpoint of the vessel. In contrast, designed draft is the height from the molded baseline to the design waterline. (Zubaly 2011, 28) From these basic dimensions, the necessary design ratios can be created. Design ratios are useful because they provide a Naval Architect or decision maker a point of reference early in the design process without being solution specific. For example, based on historical data most frigates or corvettes will have a length to beam ratio of 8.5 (Watson 1998, 67). This lets a decision maker understand some of the physical properties of a future frigate design without having to actually decide between a 300- or a 400-foot design. The design ratios that will be considered are length to beam (L/B), beam to draft (B/T) and length to draft (L/T).

Length to beam ratio is widely used in parametric ship design. This ratio represents a trade between overall speed and transverse stability. A high LBP will reduce the vessel's Froude number, thus decreasing hull resistance that is necessary to achieve high-speed requirements. (Zubaly 2011, 243) Beam tends to increase overall ship volume, which is important in draft-limited designs or designs that require a high degree of transverse stability. Vessels with a high length to beam ratio will tend to be long and narrow, while designs that have a low length to beam ratio will be more short and squat. Based on design lanes suggested by Watson, a range of length to beam ratio from 5.0 to 8.5 was considered for the seakeeping model (1998, 66). Draft-limited ship designs would be on the low end of this range, while frigates and corvettes are at the high end. (Watson 1998, 66) The length to beam ratio is a primary factor to be considered in the seakeeping performance model.

Next, beam to draft ratio is considered because it has a significant impact on transverse stability. The range of values considered ranged from 2.25 to 3.75 because this is the range for most vessels (Parsons 2003, 11-8). Vessels needing a great deal of stability will be on the higher end of the spectrum; while vessels that have incorporated other stability improving measures such as a reduced superstructure will be on the low end. The final factor is the length to draft ratio. This ratio will primarily affect longitudinal stability and bending moments that determine the structural strength necessary for longitudinal framing. The range of values considered for this factor is from 15 to 30. The low end of this spectrum is bulk carriers that have to compensate for significant bending moments to frigates on the high end. (Watson 1998, 72) These ratios are the factors that will be used to create different hull exhibiting these characteristics that will create the data needed to create the seakeeping performance model.

Once the plausible ranges of values for the model were defined, the hulls that would provide the data points could be created. A parent hull form was chosen, a method for creating variations that exhibit the desired characteristics was developed and nine unique hulls were produced to cover the possible solution space. The objective was to efficiently canvas the plausible design ranges to produce enough data points to draw reasonable conclusions from a model, while not overloading the capacity to create and analyze the data itself.

For the purposes of creating a model, there will be a single parent hull and related variants will be developed from that. The hull that was chosen was the 270-foot Famous class WMEC. This was chosen because it is the legacy platform OPC replaces, is of a similar size to OPC and has readily available information. Good processes must be repeatable. An objective of this research is to create a process that is not only applicable to the OPC program, but could be applicable to any future Coast Guard acquisition program where seakeeping is a primary operational concern. The legacy platform is a natural place to start from because it is well understood and has high quality information readily available. Most seakeeping programs require an accurate description of the design's hull geometry. These faired lines and offsets are typically not available at the conceptual stage of design. Having a set of lines and offsets from an existing asset and modifying them to represent a potential design allows an analysis to be completed at an earlier stage of design. Additionally, comparing the results produced from the seakeeping program to real world experience provides validation to decision makers that the information produced by this method is trustworthy. Finally, while no specific details of the competing OPC designs have been released, OPC is believed to be of a similar size and displacement to the legacy WMEC classes if not slightly larger. For these reasons, the decision was made to use the 270-foot Famous Class hull as the parent hull form.

The next step in creating the hull variants was to develop a method for systematically varying hulls to encompass the factors needed in the model. A key requirement for this phase was repeatability for future applications and timeliness because of the need to create so many different hulls. The first decision made was to use Microsoft Excel as a platform for manipulating the hull forms. This decision was made because of the ubiquity of this software among industry, users and acquisition commands and because the built in solver features can quickly perform the tedious work of adjusting the offsets to meet the necessary characteristics. Implementing this involved transposing the half-breadth offsets from ship plans into a spreadsheet environment; calculating volume, dimensions, displacement and design ratios from the offsets; creating a means for the solver to alter the geometry of the hull; and an objective function to guide the solver to making a hull with the desired characteristics.

The first task in implementing the method was to define the geometry of the hull within the computer environment. This was accomplished by importing the offsets from the ship plan set into a spreadsheet. Offsets themselves are merely points in three-dimensional spaces that describe the geometry of the hull form. This geometry needs to be interpreted to be useful. Interpretation was performed by coding the process for calculating the pertinent dimensions such as LBP, maximum beam, depth and volume. Draft and displacement posed a dilemma. Displacement is a function of the volume of water displaced and draft is a function of displacement and volume as well. In most plans, a design waterline provides the necessary information to precisely calculate the submerged volume and the displacement. In this situation, however, these values will be unknown and changing as Excel attempts to solve this problem. The solution implemented was to parametrically estimate the displacement in lieu of precisely calculating it. This approach was used because by increasing the information available to solve the problem, the solver was able to find a solution and the loss in precision is not as important at the early stages of the design process because other factors will most likely change meaning that an estimate at this early stage will almost always be wrong anyways. From this, the displacement and draft could be calculated. With the primary dimensions, the design ratios were determined.

Following the task of calculating the primary dimensions and design ratios, the next task was to enable a mechanism to adjust the hull in in such a manner to allow Excel to solve for a new hull with the desired characteristics. This was done using a set of shaping variables. There were three variables that were used to manipulate the shape of the hull: length, beam and depth variables. The length variable varied the spacing between hull stations. In effect, this either stretched or shrunk the parent hull to change the LBP. The beam variable applied a multiplier to the offsets. This had the effect of widening or shrinking the transverse cross-sections. Adjusting cross-sections changed not only the beam, but the volume of the hull affecting the beam as well. Finally, a depth variable was used to manipulate the spacing between transverse cross-sections. Later testing would reveal that this variable had little effect on producing the desired characteristics. These variables allowed Excel to create different hull variations from a parent hull form.

Finally, an objective function had to be created to point the solver toward creating the hull that the user desires. This task required a precise definition of how the hulls should vary from each other as well as constraints needed to appropriately bind the designs. A total of nine hulls would be produced that were intended to accurately canvas the relevant ranges of the design factors listed previously. To do this, each hull would represent a specific hull design ratio value. The range of the factors was sampled as close as possible to both end points and at the mid-point. For example, one of the hulls was needed to test the high end point for the length to beam ratio with an LB of 8.5. This variation would be done while constraining the overall displacement to isolate only effects from the factors considered. The draft was also constrained to increase the differences between the hull variants. An objective function was created that minimized the squared differences between the desired design ratio and the actual design ratio. Additionally, the squared differences between the current displacement and the objective displacement and the current controlled dimension and the desired controlled dimension were added to the objective function. In this example, the squared differences between the length to beam ratios, the displacement and the draft are summed and the solver is tasked with minimizing this objective function. Once the solver macro had run, the solution was examined and plotted. Plotting allows the analyst to verify that the hull form is plausible. This process is then repeated until all desired hull variations are created.

In conclusion, various applicable factors were identified based on their effect on seakeeping and a method for creating different unique hulls was developed. The factors were chosen from design ratios because they are solution neutral and useful in the early stages of design. Once pertinent factors were identified, hulls exhibiting these design ratios were needed. A 270-foot Famous class cutter hull was chosen because it is the legacy asset the OPC will replace and information is readily available. Variations were made to this parent hull to produce dependent hulls using Excel’s built in solver. The solver manipulated several shaping variables to minimize an objective function that was set up in such a way to produce a hull exhibiting the desired characteristics. The result of this process was nine unique hulls each representing a different point in the potential design space. These hulls would each produce data on seakeeping performance that would build a model.

2. Seakeeping Performance Calculation

With nine distinct hulls each exhibiting a unique point in the design space, the next step was to determine the actual performance of each hull. There are several methods to analyze this performance. Linear seakeeping theory was chosen because tools exist that implement this approach, it is inexpensive to use and the limitations are not such that preclude its use at an early point in the design process. The tool chosen for the analysis is SHIPMO. Developed in 1989 by Robert Beck and Armin Troesch, this program computes motions of a vessel in six degrees of freedom using the geometry of hull as input (Beck and Troesch 1990). The output of the program is a text file containing the numerical results of the calculations. This output is essentially a long list of added mass, damping coefficients, and exciting forces and moments as functions of the frequency of motion for all six degrees of freedom. Additional information includes all hydrostatic parameters and other relevant parameters such as speed and metacentric height. These are not intuitively obvious and require manipulation before they can be presented. Post-processing is required and several MATLAB functions were used to read in the data and plot it in a way that is intelligible.

Figure 9 contains a frequency response plot for the vertical motion (heave) of the ship as a function of both the wave period and the wave heading. Resonant areas can be clearly seen by the dark red color of the figure. Such areas, in other words, the indicated combinations of wave periods and wave headings, should of course be avoided in operations. Figure 10 contains a similar frequency response plot for the ship’s pitch motion. The frequency response plot for the relative motion at the stern is shown in Figure 11. This response is significant for propeller racing events. Lastly, the frequency response characteristics in roll are shown in Figure 12. It can be seen that beam to aft-quartering seas exhibit, as expected, the highest amounts of roll motion.

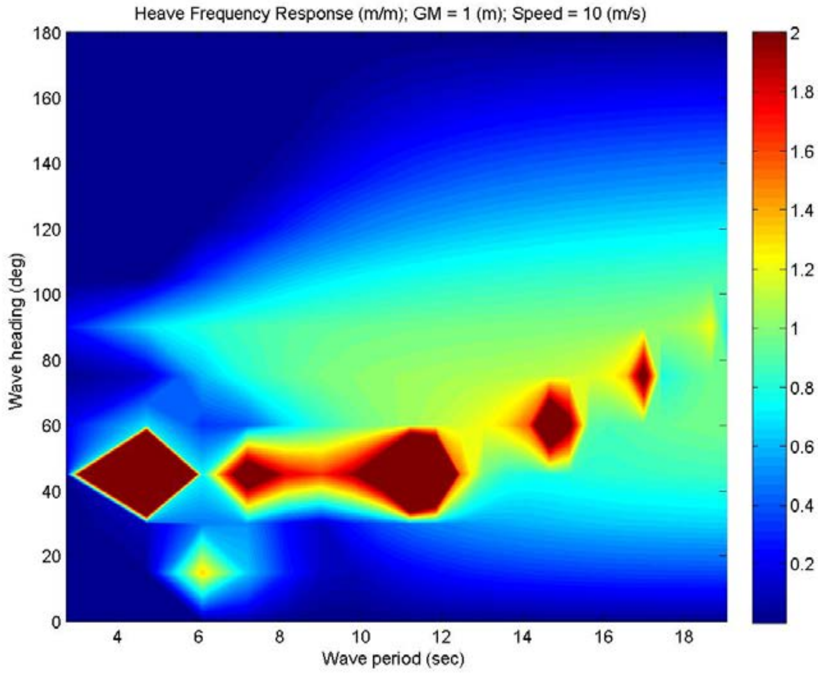

Figure 9. Heave Frequency Response

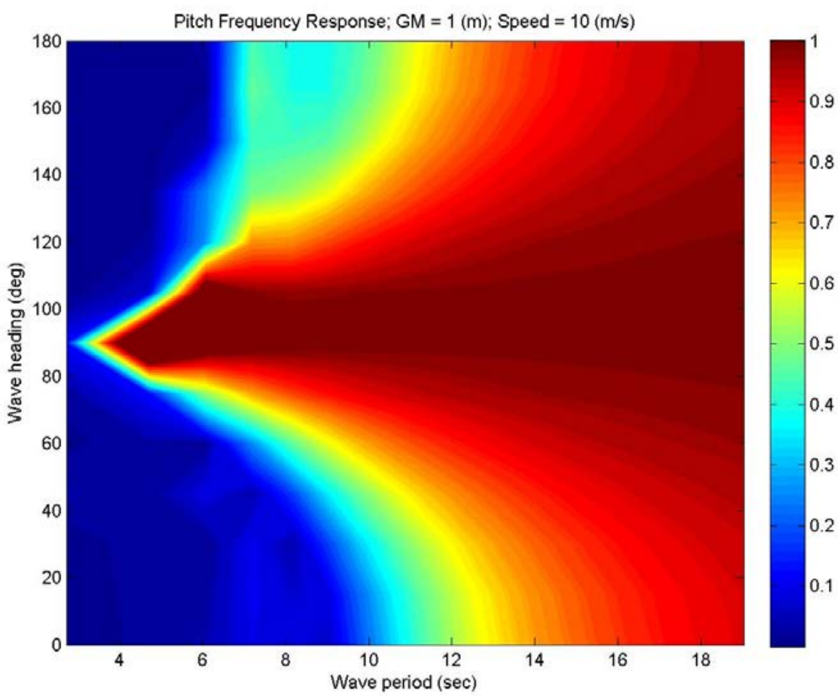

Figure 10. Pitch Frequency Response

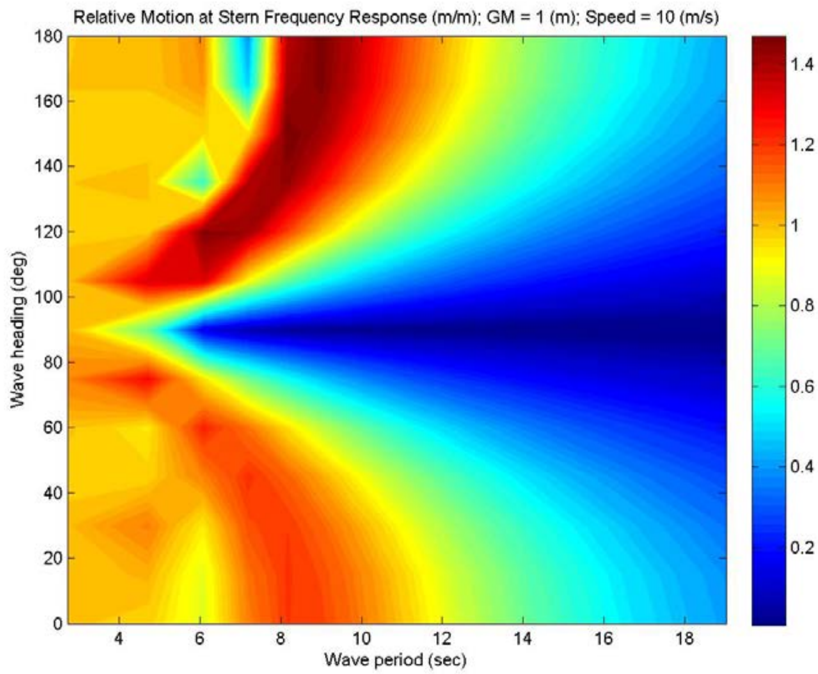

Figure 11. Frequency Response of Relative Motion at the Stern

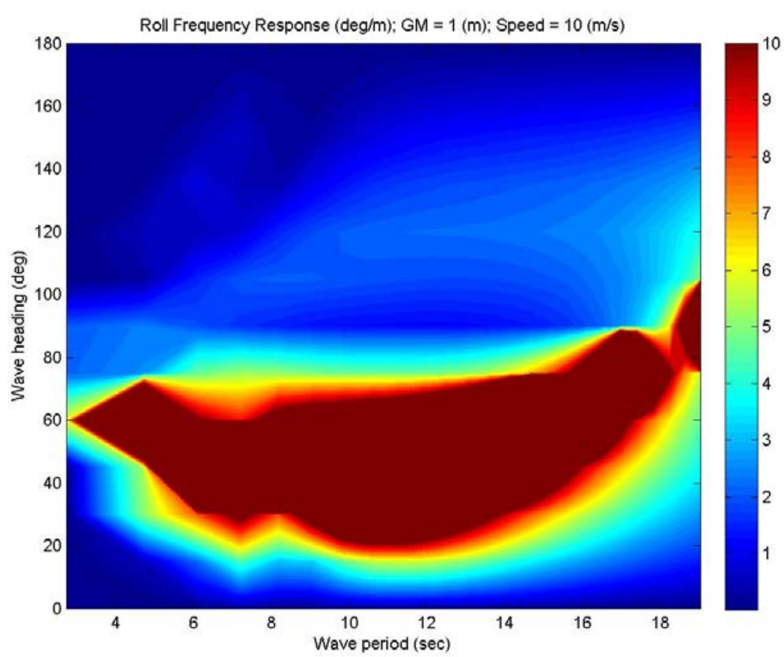

Figure 12. Roll Frequency Response

Typical random wave results are presented in the figures in Appendix A. Random wave results have been obtained by assuming a typical two-parameter spectrum and long-crested seas. Each figure corresponds to a different seakeeping criterion. The polar plots clearly indicate regions of operations that should be avoided since they violate the assumed criterion. All such figures can be superimposed and summarized in a single graph containing the final operability diagram based on all criteria

Figure 13 contains the primary product of this effort. The blacked out areas represent vectors that will violate one or more of the seakeeping criteria. All headings are degrees relative to the wave direction and the lines extending radially are the velocity of the ship given in meters per second. The operational index is simply the ratio of the vectors that do not violate any of the criteria to the total amount of vectors. In the case presented in Figure 13, 82% of the total performance envelope is available to be used by the ship operator.

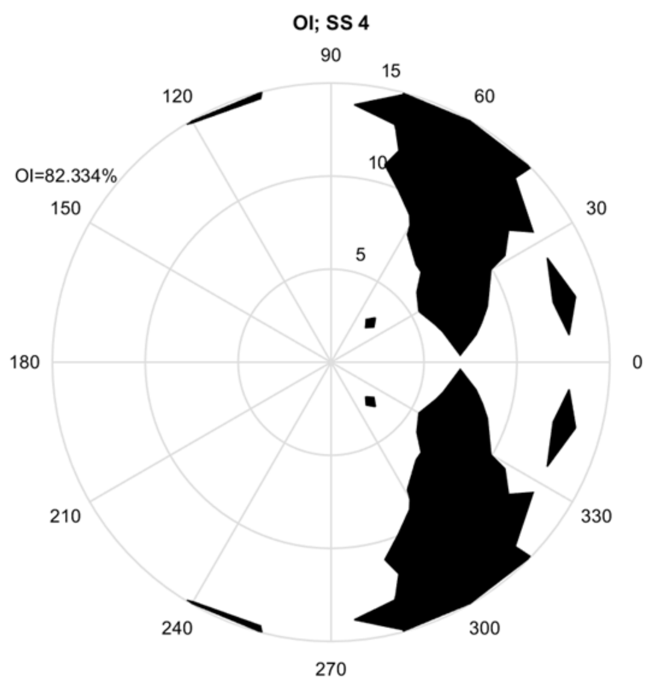

Figure 13. Operational Index Polar Plot for Sea State 4, All Headings Are Relative to the Wave Motion and Velocity is Given in Meters per Second

While only a sliver of the envelope is truly necessary for operations, a higher operational index would allow an operator greater tactical flexibility to perform the needed operational activities in ways that do not disrupt the mission at hand. For example, a cutter is attempting to intercept a drug running “go-fast” vessel and is on an intercept course of 0 degrees relative to the ocean waves at 18 knots. In order to launch the small boat to intercept the smugglers successfully, most ship handlers would slow down and create a lee at the boat launching position resulting in potentially reducing speed to five knots and altering course to starboard to a relative heading of 330 degrees. In this case, the maneuver has lost ground to the drug runner reducing the probability that the intercept takes place, ultimately lowering mission effectiveness. If the cutter did not have to reduce speed or change course to launch the small boat, the mission effectiveness would no longer be adversely affected. This example allows one to make the connection that a higher operational index is to be preferred.

For any given hull, this process can be repeated for all given sea states. This function is shown in Figure 14. As expected the ship’s seakeeping performance degrades as the sea state increases. The composite operational index is the convolution of the operational index function and the probability density function of sea state occurrences in a given operational area like that shown in Figure 15. COI accounts for the performance of the ship at a given sea state and the likelihood that an ocean is in said sea state. A particular ship will only have one COI for a particular operational area. The final result of these calculations is presented in Table 2 for the Famous class cutter. COIs and the associated figure of merit assess the level of seakeeping performance for any given hull.

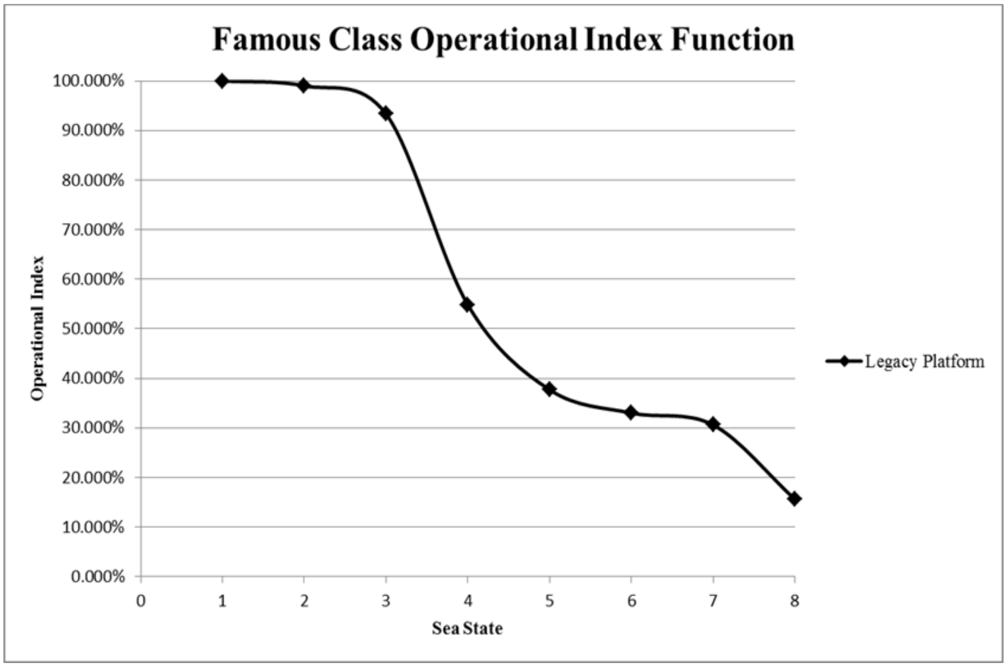

Figure 14. Famous Class Operational Index as a Function of Sea State

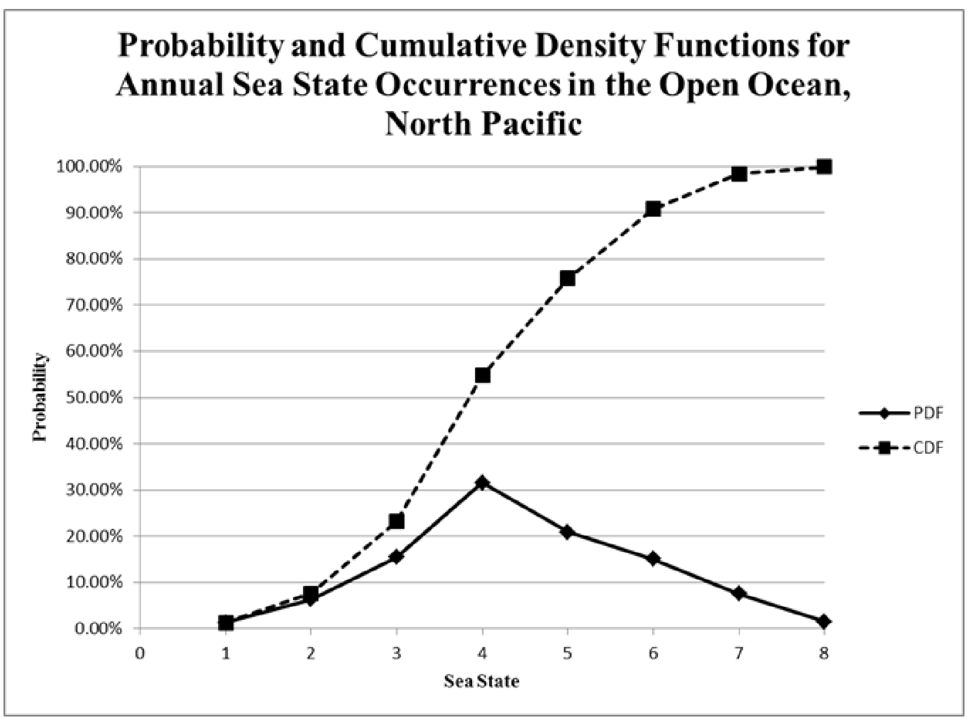

Figure 15. Probability and Cumulative Density Functions of Annual Sea State Occurrences in the Open Ocean, North Pacific. Adapted from Lewis (1989, 28).

Table 2. Composite Operational Index and Figure of Merit for Famous Class

	North Pacific	North Atlantic	Caribbean Sea	Bering Sea	Figure of Merit
Famous Class	54.84%	58.92%	89.26%	51.31%	63.58%

3. Model Regression

With COIs for each of the nine variant hulls, the data exists to create the seakeeping performance prediction model. The question arises about what is best to model either the figure of merit or each COI. Models predicting COIs for each operational area were decided upon because a decision maker might desire that level of detail. Performance prediction models are useful because they allow for an assessment of seakeeping performance without the need for a detailed hull design. The downside of models is that they are only as reliable as the input data. The limitations of linear seakeeping theory are still present and the error inherent to the regression process only adds more uncertainty to the prediction. Accepting this, regression is still a powerful tool that allows for some limited predictions of how changing design parameters will affect the seakeeping performance of a future ship design.

Linear regression is used to create linear models with one or more predictor variables that will output a response to some degree of uncertainty. First, the major assumptions made in applying this technique to the problem are that the response will be linear and that the truly predictive characteristics are being considered in the state space. Linearity assumes that a change in one characteristic will have a proportional change in the response. The predictors consider typical design ratios that are frequently used by ship designers and are widely considered to have an effect on ship motions. Each measure is the ratio of basic hull characteristics such as length to beam, beam to draft and length to draft. These characteristics define the shape of the hull to a large degree. While other factors could influence motions, that additional information will most likely not be known with enough certainty early in an acquisition program to influence decisions. The three design ratios will be considered as predictors for a model. From these three possible predictors, several models can be considered. The criteria used to select the model will consider both the r-squared adjusted statistic and the standard deviation. R-squared adjusted statistic measures explained variance while penalizing overfitting. Explained variance is important because it represents how much of the observed variance in the data is caused by changes in the predictors. A higher percentage means that more of the error is explained by the model and that the model is accurate. The downside to this is that models can be over-fit. This means simply that by adding enough predictor variables, variance can be eliminated. To balance these two competing ideas, the adjusted r-squared statistic is reduced as the amount of predictors is increased. In addition to adjusted r-squared, model standard deviation will be used to evaluate models. Standard deviation provides a measurement of the uncertainty associated with the predictions made using the model. A smaller standard deviation means the model is precise. Ideally, the model would have a high adjusted r-squared statistic and a low standard deviation. The actual regression will be completed by statistical software.

Statistical software can calculate the statistics and coefficients for all possible models. This information was then used to determine the most appropriate model. Ultimately, the length to beam ratio and length to draft ratio were chosen as the predictors because they had high adjusted r-squared percentages and relatively low standard deviations as shown in Table 3. These predictors had similar levels of performance across the North Pacific, North Atlantic and Bering Sea operational areas. The Caribbean Sea model was an outlier because of the low adjusted r-squared statistics across all possible models. This could have been because all the data points had high COIs in this area or it could be due to other factors. Whatever the cause, uniformity in model form was chosen to avoid unrealistic solutions. The actual model forms are shown in Equations 12 through 15. These models will be programmed into an Excel workbook and constitute the seakeeping performance prediction.

Table 3. Parameters for COI Prediction Models

Model	Predictors	R-Squared Adjusted	Standard Deviation
North Pacific	Length-Beam, Length-Draft	76.0%	0.0314
North Atlantic	Length-Beam, Length-Draft	78.4%	0.0308
Caribbean Sea	Length-Beam, Length-Draft	48.9%	0.0171
Bering Sea	Length-Beam, Length-Draft	77.5%	0.0333

$$\text{North Pacific COI} = .2264-.01682(\text{Length/Beam})+.028916(\text{Length/Draft}) \quad (12)$$

$$\text{North Atlantic COI}=.29573-.016079(\text{Length/Beam})+.026777(\text{Length/Draft}) \quad (13)$$

$$\text{Caribbean Sea COI}=.80184-.010230(\text{Length/Beam})+.010755(\text{Length/Draft}) \quad (14)$$

$$\text{Bering Sea COI}= .16866-.016992(\text{Length/Beam})+.030486(\text{Length/Draft}) \quad (15)$$

4. Cost Estimating Model

Performance always comes with some cost and the design tradeoff is always between fielding an effective system at an affordable price. Cost is certainly something every decision maker is going to want to know and must be incorporated into the analysis. Creating a cost model is outside of the scope of this research, so an existing model will be used. Kirk Loftus developed a multi-variable parametric cost model in 1999 for conventional U.S. Navy surface ships (1999, 61). This model uses displacement, length to beam ratio and number of engines as predictors. The displacement, length and beam ranges are wide enough to consider most possible Coast Guard cutter designs. Number of engines is a function of power required for each design. This is an important consideration and tradeoff with regard to seakeeping performance. In general, a larger ship is going to have greater seakeeping performance, but will most likely need more power. The cost model is presented in Figure 16 along with associated specifics.

The Multivariate *MV2* Model:

***AVGCOST* (CY99M$) = -693.76 + 0.0207*_DISP_ +**
106.262*(*LEN/BEAM*) + 86.6332*_ENGNUM_

Where:

DISP = Light Displacement in tons.
LEN = Length in ft.
BEAM = Beam in ft.
ENGNUM = Number of Propulsion Engines.

Allowable Range for independent Variable:

Light Displacement: 75 to 28233 tons.
Length: 81 to 844 ft.
Beam: 18 to 103 ft.
Number of Engines: 1 to 5.

Cross-validated Statistics:

Adjusted Coefficient of Determination:	37.2%
Coefficient of Variation:	74.1%
Residual Standard Error:	308.1 (CY99M$)

Figure 16. Multivariate Conventional Ship Cost Model and Specifics. Source: Loftus (1999).

There are two aspects of the multivariate model that require integration into the decision making tool are converting to the present value of money and estimating the number of engines. Converting to the present value of money is simple. The latest inflation tables were obtained from the Office of Management and Budget and applied to the tool to convert from 1999 dollars to base year 2016 dollars. Applying the expected number of engines is more involved.

The number of engines is a function of the power required to make top speed. To estimate this, an equation for effective power in salt water was used as shown in Equation 16 where; C is the total resistance coefficient, a constant; S is the wetted surface area and V is the velocity in knots. Effective power (PE) is the power needed to propel the ship through the water at a given speed neglecting any losses or inefficiencies in the shafting or propeller (Zubaly 2011, 264). Added to this is an inefficiency factor of 25% to account for likely propeller and shafting losses, as seen in the following equation (Watson 1998, 163).

$$PE(kW) = 0.06097 * C_t * S * V_k^3 \tag{16}$$

The estimate of total power required is then used to estimate number of propulsion engines to complete the inputs for the cost model. While there are many options for propulsion subsystems such as gas turbines and electric motors, conventional marine diesel engines were selected because there has to be some baseline in order to compare the relative cost of the different designs, diesel engines are on the legacy ships and are widely expected to be used on the OPC. To set an even baseline, the ALCO 251F marine diesel engine was chosen as it is closely related to the engines in use on both legacy platforms. The selection of an engine allows for a design's power requirement to be incorporated into the cost model.

In conclusion, the chosen cost model will illustrate the differences between designs and highlight the tradeoffs made between performance and cost. Admittedly, the cost model is not ideal; the standard error is large relative to the expected costs and the power estimation formula is inexact. These inadequacies collectively mean that the estimate for any specific design is likely to be incorrect; however, the differences between the costs of different designs do show the trades that can be made between cost drivers and performance enhancing features. When cost and performance are estimated for large numbers of designs, overarching trends will become visible and a great deal of information can be gleaned.

C. UNCERTAINTY

Without delving too much into the cliché, the future is unknown and it is impossible to predict with any accuracy all of the events and crises involved in bringing an acquisition program from an idea to a fielded system. Risks, for example, are typically presented as probabilities because there is always a chance that that particular problem might not become an issue for the project. Design characteristics too are malleable and it can be difficult to know exactly why a specific value was chosen or not. These examples are describing the uncertainty omnipresent at the beginning of an acquisition program. This uncertainty prevents a deterministic point estimate of cost or performance from ever being correct. Only by acknowledging this uncertainty can useful information be extracted for a decision maker. Uncertainty is incorporated into the analysis by applying Monte Carlo simulation.

Monte Carlo simulation is the repetition of many trials using random values drawn from the same underlying probability distributions defined for each design characteristic. Uncertainty is accounted for by defining the design characteristics as probability distribution functions from which random values are drawn instead of known values. For this analysis, all input distributions were defined as triangular distributions. This function is a triangle bounded by three points: the minimum, maximum and most likely values. While other distributions might more accurately describe the likelihood of choosing certain characteristics, the triangular distribution has the advantage of simplicity. A decision maker will either know or have someone who knows, with a great deal of likelihood, these values. The user will enter these three points into a triangular distribution function. Excel's random number generator provides the randomness that will pull random design characteristics from the user defined functions. Each set of design characteristics represents a unique outcome for the offshore patrol cutter program.

Repeating this many times will show the broad spectrum of possible program outcomes. The two questions that a decision maker is looking to answer are will this system perform satisfactorily and will it cost more than is budgeted? Any single trial will be of limited value because it will only answer each question in the affirmative or the negative. The answer from one trial could easily be contradicted by the next. Large numbers of trials, such as 30,000 in this case, go beyond merely reporting these outcomes to providing probabilities that each outcome will occur. This broad perspective will come once the data is aggregated.

The 30,000 results from the Monte Carlo simulation will only make sense when they are placed within a broad framework. The two risks that need to be quantified are performance and cost. Each trial is a possible ship design with an associated figure of merit and estimated cost. To aggregate the data, each data point will be binned based on its respective FOM and cost. Probabilities can be calculated that a design will fall within a specific bin. The probabilities can be plotted as cumulative distribution functions or probability distribution functions. Performance risk is the probability that a design will have a smaller figure of merit than the Famous Class cutter, the OPC is replacing. This is calculated by counting the number of trials that have a smaller FOM than the legacy platform. Cost risk is calculated in a similar way. Cost is presented as a PDF because a model will be fit to the data. The model is helpful because it provides more information than a simple reporting of an outcome. For example, if there is a high degree of cost risk at the target cost of $329 million one might be interested in what the mean cost is or even what the cost is for a defined level of risk such as an 80th percentile cost estimate. A model can provide all of these answers. The cost models are assumed to be lognormal distributions and are calculated using the Excel solver and least square error regression. The twin figures of cost and performance risk are the primary outputs to a decision maker.

In conclusion, all of the disparate pieces of analysis can be brought together in an Excel based decision support tool. The tool is important because the end result of the analysis is the process through which the tradeoff is made, not necessarily the final determination of risks. This is important because the actual values for design characteristics are known only to a very few individuals within the program and certainly not to the researcher. It is also important because some of the analysis techniques require technical knowledge that might not be readily available within the program office. If the process could be hard coded, then it could be used within a program without someone needing to know how to do the analysis themselves. Excel was chosen because of its ubiquity on military computers. This tool will fulfill all four requirements previously identified.

The tool contains three major components: data entry, data processing and data presentation. A screenshot of the data entry menu is shown in Figure 17. Users can enter minimum, maximum and most likely estimates for key parameters affecting system design and program characteristics. Users can also enter their preferred confidence level and can adjust the decision making weights to prioritize performance within operational areas. Almost every aspect of the analysis can be adjusted by the user. These parameters define triangular distributions from which random values are drawn. The next component is the data processing subsystem. Data processing includes all of the models, plots and functions that are used to take the inputs from the user and produce the analytical products with a minimum of user interaction. Finally, data presentation will present the results of the analysis to the user. A dashboard was used to communicate the results of the analysis. Care was taken to present enough information to communicate the performance and cost risks, while not overwhelming the users. A screenshot of the dashboard is shown in Figure 18. These three components form the basis of the decision making tool.

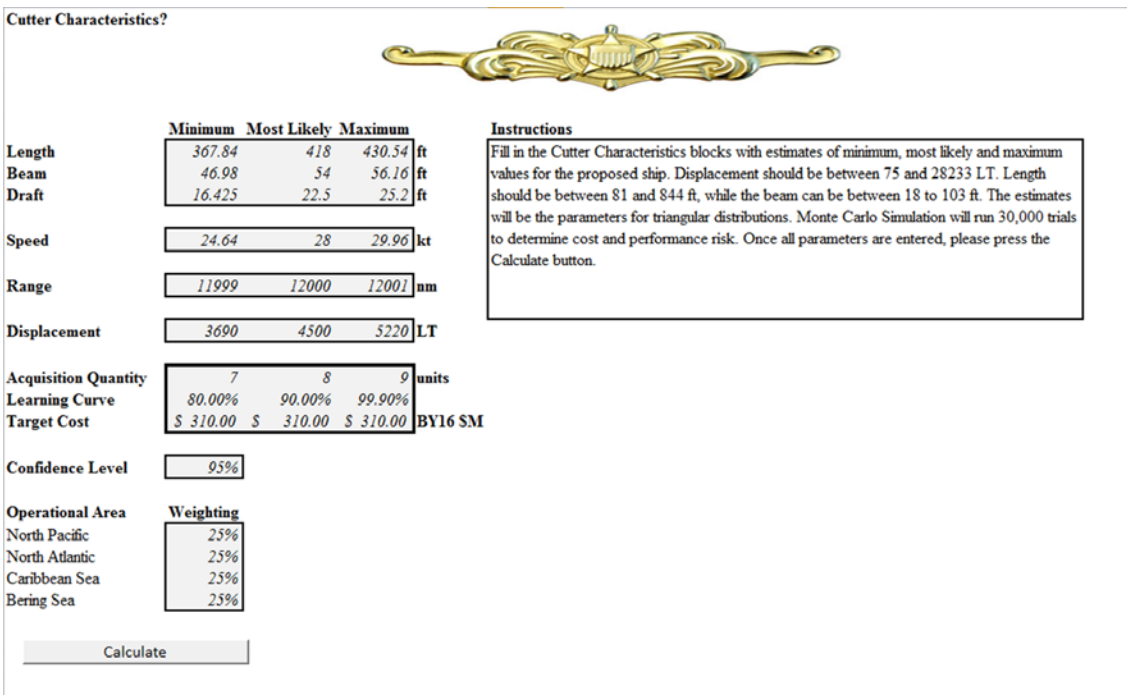

Figure 17. Decision Support Tool Data Entry Screenshot

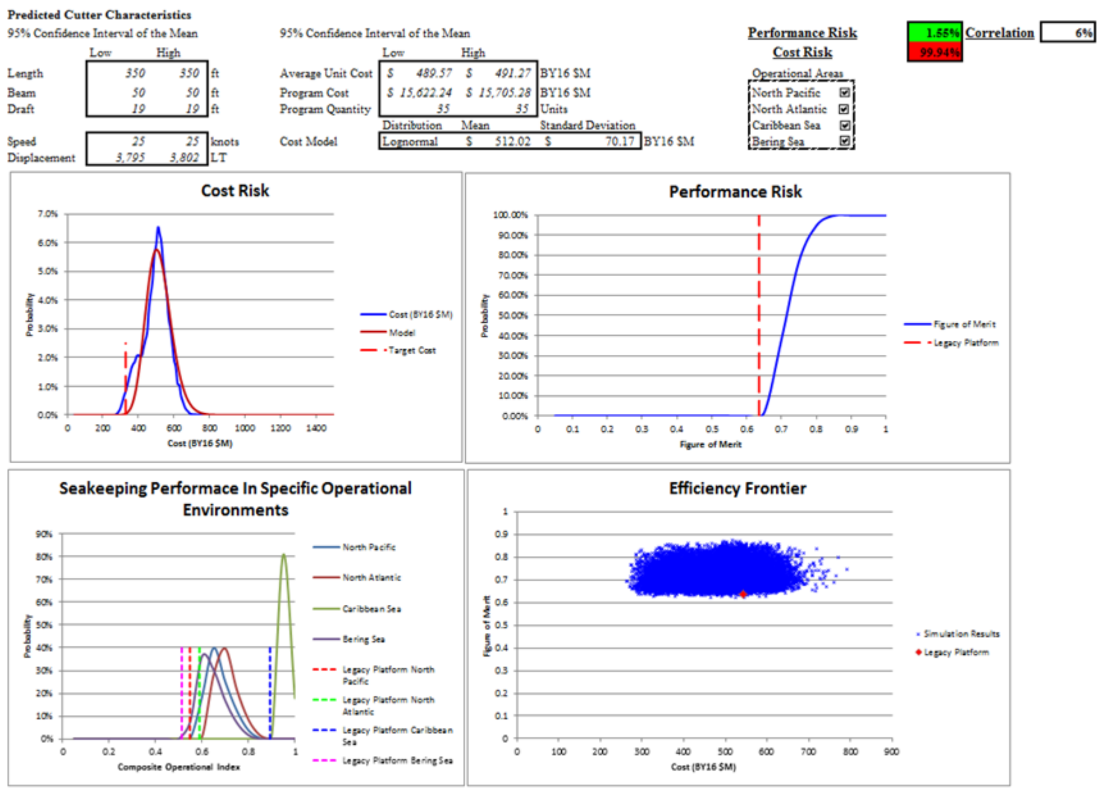

Figure 18. Decision Support Tool Dashboard Screenshot

The threefold approach of considering risk, seakeeping performance and uncertainty created a tool that takes as input a conceptual view of the future system and outputs the expected performance and cost risks. Risks were defined and methods for calculating them were proposed. A seakeeping performance prediction model was created from data created by applying linear seakeeping theory to nine representative hulls. Uncertainty was considered and Monte Carlo simulation was applied to gain a broad perspective. This quantifies the performance and cost risk. A decision maker can see the connection between trades in design characteristics to achieve performance goals, while having a reasonable chance of maintaining the budget.

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IV. ANALYSIS

The utility of a tool is often only perceived after seeing the ways it can be used. Demonstrating the usefulness of this tool is much different from making a critique of the Offshore Patrol Cutter program. Results are only as accurate as the input data. Without access to sensitive design characteristics, it would be difficult to make a specific judgement and recommendations for the OPC. Projected design characteristics can be used to illustrate how the tool would be used within a program office, how the results would be analyzed and how it can be used to empower trade studies.

The first step is to define the primary design characteristics and range of the OPC. This information is not available for several reasons. First, the OPC program has an ongoing competition among Bollinger Shipyards Lockport LLC, Eastern Shipbuilding Group Inc. and General Dynamics, Bath Iron Works who have all been awarded preliminary design contracts (United States Coast Guard Acquisition Directorate 2016). This competition precludes ready access to information to avoid leaking sensitive information. In addition, each of the three contractors has their own design that is unique and distinctive from the others. This leads to uncertainty over exactly what the OPC's design characteristics will be. One approach is to take a very broad view. The Coast Guard Acquisition Directorate states that the OPC will fill the capability gap between the National Security Cutter and Fast Response Cutter (2016). Using this view, the OPC would probably be larger than the FRC, but smaller than the NSC. Ultimately, this approach is unsatisfying because the smaller designs are unrealistic due to aviation, communications and habitability requirements. These smaller designs have lower costs that skew the average unit cost down in a misleading manner. Another option is to adopt someone else's estimate. Barton Philpott and Matthew Weber in their study on OPC affordability examined publicly available information on competing OPC designs and synthesized an estimate of what the projected design characteristics would be (Philpott and Weber 2015, 51). This information has been adapted into and presented in Table 4.

Table 4. Projected OPC Design Characteristics Adapted from Philpott and Weber (2015).

	Minimum	Most Likely	Maximum
Length (ft)	320	360	370
Beam (ft)	45	52	54
Draft (ft)	14.5	20	22.5
Speed (kts)	22	25	27
Displacement (LT)	3100	3800	4500

This estimate of size may not be completely accurate, but it is the best prediction publicly available. With entering arguments defining the range of possible designs, this data can be entered into the decision making tool and the results can be analyzed.

A. RESULTS

After entering the design parameters and running the model, the user is presented with a large amount of information in a dashboard screen. The dashboard takes the data produced from the model output and distills it into information that is useful to a decision maker. The user is ultimately looking for a risk assessment of the OPC design as previously defined. This answer is provided along with much more information that provides nuance to the program office. Immediately, the user wants feedback on the calculated risks, which is shown in Figure 19. This is very striking because it shows that there is a very low performance risk, while the cost risk is extremely high. By themselves, the numbers are only so descriptive. A user should see these numbers as a warning that the current design characteristics achieve a high level of performance, but that might come at the cost of being unaffordable. Once this information is understood, the user should analyze the results that produced these numbers.

Performance Risk	**1.53%**	**Correlation**	**5%**
Cost Risk	**99.96%**		

Figure 19. Performance and Cost Risks and Correlation from the Dashboard

1. Performance Risk

Seakeeping performance is primarily a function of the geometry of the hull. In general, a larger ship will have better performance in this regard. From the dashboard, there is a very low level of performance risk. This risk is low because the expected ship is fairly large. Figure 20 shows the mean cutter characteristics. The Monte Carlo simulation produces 30,000 possible ships with characteristics randomly drawn from the user defined input functions. The predicted cutter characteristics express a point estimate of what the OPC will be like. Notice that while this is close, it is not exactly what the most likely estimate is. This is important to consider because it makes sense that an OPC much larger than the legacy platform will perform better than what it is replacing.

Predicted Cutter Characteristics

95% Confidence Interval of the Mean

	Low	High	
Length	*350*	*350*	ft
Beam	*50*	*50*	ft
Draft	*19*	*19*	ft
Speed	*25*	*25*	knots
Displacement	*3,797*	*3,803*	LT

Figure 20. Predicted Cutter Characteristics from the Dashboard

Knowing that the OPC will perform better than the legacy platform is of limited value. Figure 21 shows the plot of the figure of merit CDF. This graph shows that 93% of the ships had a FOM between .7 and .8. There is a very large probability that the proposed OPC will increase the figure of merit from the legacy platform by .07 to .16. In operational terms, this means that with all operational areas being equally weighted there is a 70 - 80% probability that at a random moment the OPC will be capable of performing any of the three critical missions from a seakeeping perspective. This represents a sizeable increase in capability and suggests that potentially there is room to reduce performance to increase affordability.

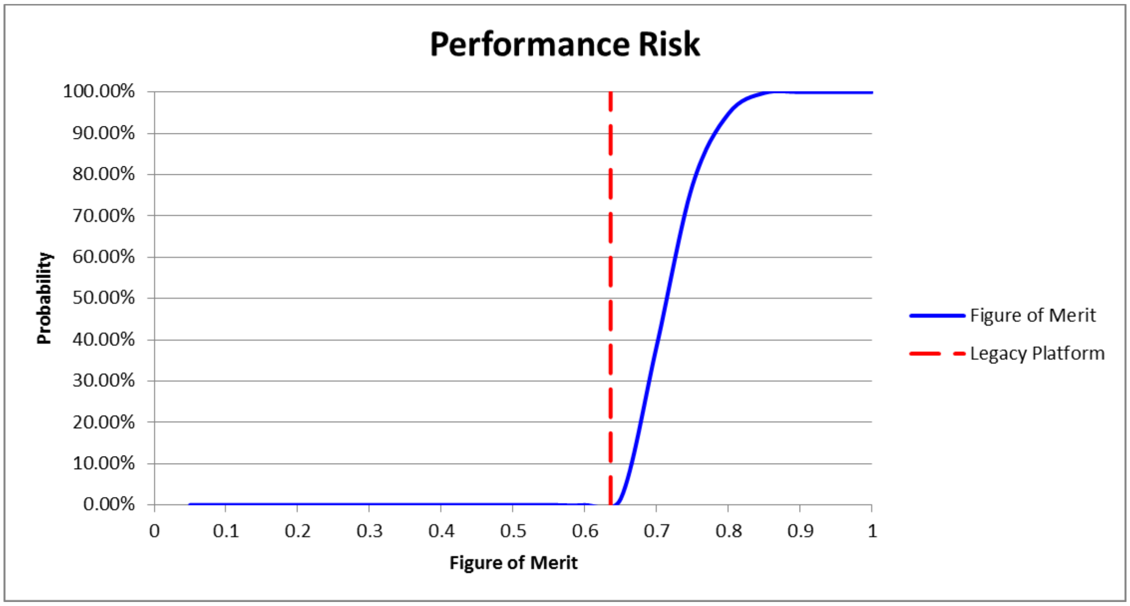

Figure 21. Performance Risk Plot from the Dashboard

2. Cost Risk

While there was a very low level of performance risk, there was a significant amount of cost risk. Cost risk is the likelihood that the average unit cost will exceed the $329 million BY16 target cost. Based on the Monte Carlo simulation results, there is a 99.96% probability that this target cost will be exceeded. While this level of certainty might seem unreasonable, the actual estimated cost is reasonable and should inspire a corrective action to maintain program affordability.

Without having the target cost as the point of reference the projected average unit cost should be reasonable to a well-informed observer. Figure 22 reports the mean average unit costs from the Monte Carlo simulation. With 95% confidence, the expected OPC average unit cost will be between $490 and $492 million. Consider that based on the expected OPC characteristics, the proposed ship will be 85% of the size of the NSC. Also, consider that the average unit cost of the NSC is $695 million (O’Rourke 2016, 3). Comparing the two programs, it would seem that this cost estimate is not outside of the realm of possibility.

95% Confidence Interval of the Mean

	Low		High		
Average Unit Cost	$	*491*	$	*492*	BY16 $M
Program Cost	$	*12,343*	$	*12,386*	BY16 $M
Program Quantity		*25*		*26*	Units

Figure 22. Program Cost Estimate Specifics

If one accepts that the $490 million estimate could be realistic, the program office should consider taking steps to reduce the cost risk. Figure 23 shows the simulation results, a lognormal cost distribution that has been fitted to the data and where the target cost is relative to both of these. To reduce risk, the center of the cost distribution must be shifted to the left by reducing costs. Cost reduction should consider potential cost drivers and ways to reduce cost in a way not too detrimental to seakeeping performance.

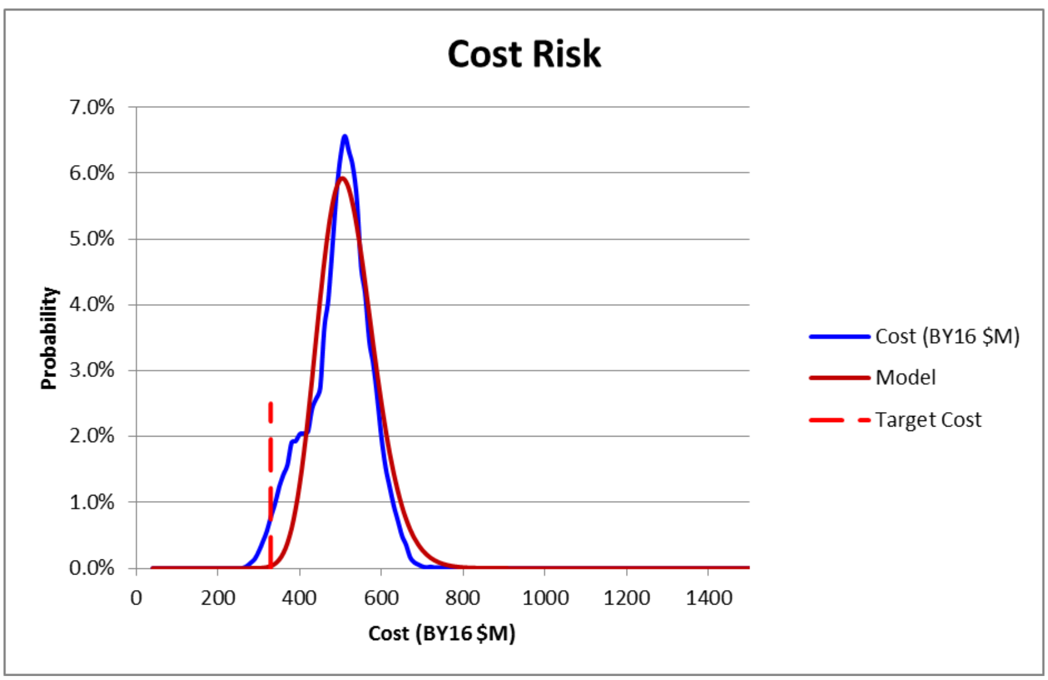

Figure 23. Cost Risk Plot from the Dashboard

B. TRADE STUDIES

Once a potential risk is identified, the natural response of a program manager is to investigate potential options to reduce this risk to tolerable levels. The first step to identify better options is to find points of influence within the design that reduces cost, while not adversely impacting seakeeping performance too much. Of the design characteristics, length appears to be a viable candidate for consideration. From the seakeeping performance prediction models, length to beam ratio has a negative influence on seakeeping while length to draft ratio has a positive influence. Draft is limited on this design because of the constraints imposed by homeport facilities. Length and displacement are also cost drivers. Reducing length and displacement will directly reduce costs. Smaller ships will require less power, but the relationship between size and power is not linear and so there is less reduction in cost from this perspective. Creating a reduced size OPC should be considered as a possible course of action. Reducing the OPC in size by 15% would still create a system that is slightly larger than the legacy platforms it would replace. The design characteristics for the reduced size OPC design are given in Table 5.

Table 5. Reduced Size OPC Characteristics

	Minimum	Most Likely	Maximum
Length (ft)	272	306	315
Beam (ft)	45	52	54
Draft (ft)	14.5	20	22.5
Speed (kts)	22	25	27
Displacement (LT)	2635	3230	3825

The resulting expected OPC characteristics are shown in Figure 25. Of immediate interest is that the cost risk has been substantially reduced as illustrated in Figure 24. This trade has lowered the cost risk, but at the cost of an increased performance risk. While there is a 36% chance that the design will perform worse than the legacy system, 63% of the designs will have a FOM between .7 and .8 as plotted in Figure 26. This means that while more instances of poorly performing designs exist, a majority of the designs will increase performance. Managing this increase in performance risk means that seakeeping should be incorporated throughout the design process to ensure that unsatisfactory outcomes are avoided.

Performance Risk	**36.41%**	**Correlation**	**7%**
Cost Risk	**24.33%**		

Figure 24. Performance and Cost Risks for a Reduced Size OPC

Predicted Cutter Characteristics

95% Confidence Interval of the Mean

	Low	High	
Length	*298*	*298*	ft
Beam	*50*	*50*	ft
Draft	*19*	*19*	ft
Speed	*25*	*25*	knots
Displacement	*3,228*	*3,234*	LT

Figure 25. Reduced Size OPC Characteristics

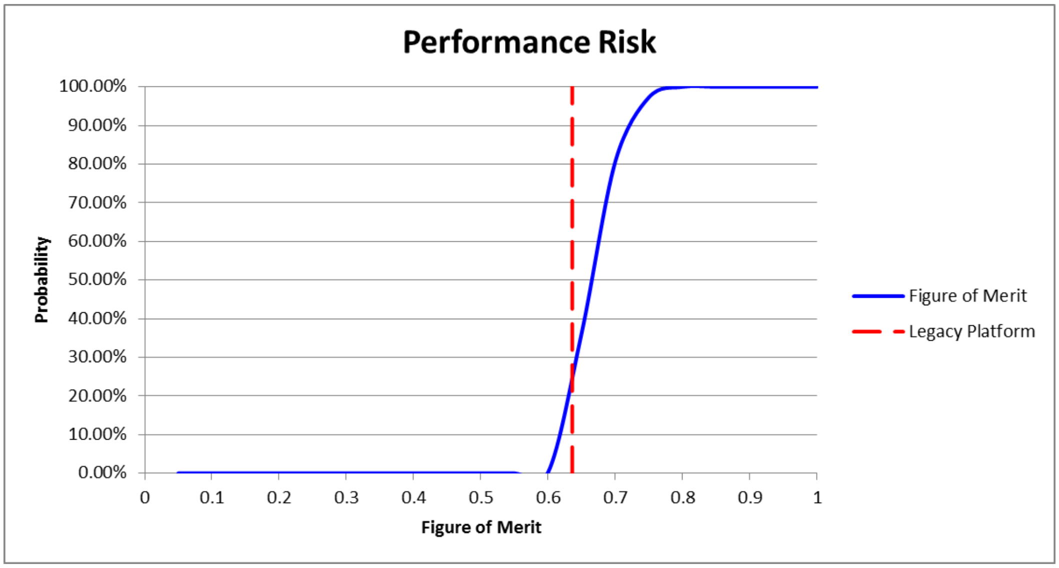

Figure 26. Performance Risk Plot for Reduced Size OPC

More performance risk is the price of reducing the cost risk. The reduced size OPC lowers the cost risk from 99% to 24% as shown in Figure 28. Mean average unit cost is likewise reduced from $490 million to $275 million in Figure 27. The tangible benefit of this is that achieving the target cost seems much more likely. Affordability is an important program objective that is rightly prioritized because achieving the full program acquisition of 25 cutters is vital to the future of the Coast Guard surface fleet due to the need to provide enough ships to maintain an effective maritime presence.

95% Confidence Interval of the Mean

	Low		High	
Average Unit Cost	$	*275*	$ *277*	BY16 $M
Program Cost	$	*6,927*	$ *6,969*	BY16 $M
Program Quantity		*25*	*26*	Units

Figure 27. Reduced Size OPC Cost Estimate Specifics

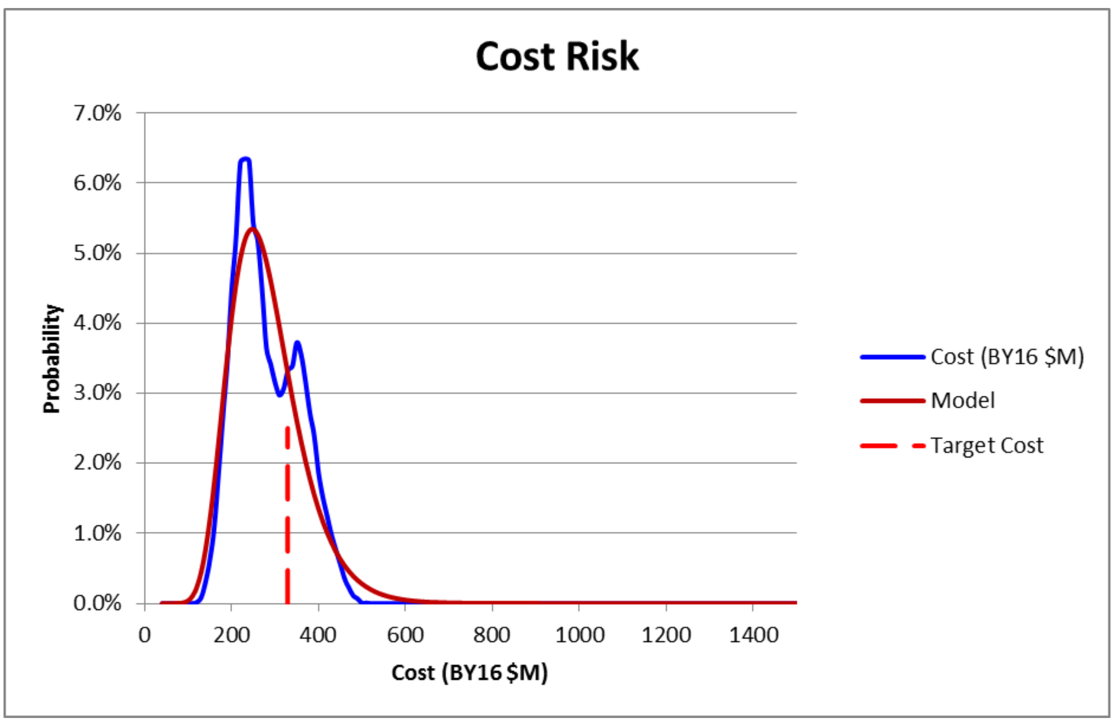

Figure 28. Cost Risk Plot for a Reduced Size OPC

While there are many reasons why a larger vessel might be necessary, one should seriously question what is pushing the size of the system larger. The aviation and small boat support requirements are no different than the legacy Famous class cutter. Weapons systems and sensors will likewise be similar to those on the Famous class. Communications subsystems will most likely be improved significantly, but is 90 extra feet of length truly necessary to effectively integrate these subsystems? The reduced size OPC is smaller than the notional designs, but still larger than the Famous class. From the seakeeping performance perspective, a functional design that improves performance should be achievable even though it is more risky. Ultimately the program manager should use this tool and any other tools available to corroborate information and make the best decision possible with the available information.

This example has demonstrated the potential utility of a seakeeping performance prediction model and decision support tool. Applying notional OPC characteristics to the tool identified potential cost risks. Adjusting the proposed characteristics allowed the PM to balance cost and performance risk tradeoffs. This tool provided a capability that PMs did not have before, the ability to predict seakeeping performance without having a detailed hull design. The analysis also presented an alternative method for quantifying seakeeping performance through the Composite Operational Index, which takes the discussion of seakeeping performance away from a description of performance in a given sea state, which can be a vague proposition, into a measure tied to expected performance in an operational area. The decision support tool provided an assessment of both cost and performance risk. A high level of cost risk with very limited performance risk could suggest that some performance risk could be accepted to reduce the potentially high cost. This risk assessment was used by the PM to test a different course of action. Adjusting design characteristics, length and displacement, the level of cost risk was lowered for a modest increase in performance risk. This tradeoff study suggests that compromising on a smaller design might involve less overall risk to the program.

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V. CONCLUSION

The Offshore Patrol Cutter program is vitally important to the future of the Coast Guard. This system will form the backbone of the service's offshore maritime presence. The 25 OPCs will be the primary assets performing offshore search and rescue, living marine resources protection and drug interdiction. The Coast Guard's ability to perform these missions in the future will depend on the effectiveness and affordability of the OPC. An OPC that cannot perform its required missions efficiently will leave key mission gaps in many of the most tasking operational environments. An expensive OPC cannot be purchased in the quantities necessary and will likewise leave mission gaps. The program office must carefully balance both of these competing demands.

Balancing performance and affordability is an exercise in risk management. Risk is the uncertainty about whether or not the fielded system will be suitable for its intended use. Uncertainty is proportional to one's ability to influence the design. Early in the ship design process, a PM has the maximum amount of control over the design and pays the lowest price for changing the design. This freedom comes at the cost of uncertainty. There is simply not enough information to make definite pronouncements about either cost or performance. Assembling the requisite information requires time and money and makes changing the design incrementally more difficult. An ability to reduce uncertainty without requiring too much information could lead to a more efficient design. Performance and cost models can quantify risks, which removes some uncertainty at a point when design changes are inexpensive.

Seakeeping is an important aspect of OPC performance. The three core OPC missions of search and rescue, living marine resources protection and drug interdiction require operational activities such as launching helicopters or small boats that are predicated on a limited amount of ship motions. Seakeeping is the study of the motions of a ship in ocean waves. A popular and efficient method for quantifying the seakeeping qualities of a ship is to utilize linear seakeeping theory. The advantage of this approach is that it produces a quantifiable result and can be completed quickly and affordably using computer programs. A key disadvantage is that the assumptions made to allow the calculations to be done quickly and cheaply add uncertainty to the results especially at higher sea states. Another problem with linear seakeeping theory is that detailed hull geometry is required. Early in an acquisition program, this level of detail in a hull design is not often available. To effectively aid the program office a method must be created to predict the seakeeping performance of a notional design even if the details are incomplete.

A seakeeping performance prediction model was developed to quantify OPC performance risk. Nine hull variants were created from the hull of the legacy Famous class cutter. Linear seakeeping theory was applied to each hull and the seakeeping performance was quantified using the operational index. This measure of performance was transformed into a measure of effectiveness by applying the probabilities that different expected operational areas experience the sea states thus creating the composite operational index. These data points can be used to create a model using linear regression. This model uses basic design characteristics such as length, beam and draft to predict the COI of notional designs. Performance is only one half of the competing demands and cost must be considered as well.

A cost estimation model was chosen to quantify OPC cost risk. Performance and cost are always related and greater performance will always come with a greater cost provided that all designs are efficient. A previous thesis produced a cost model that was used in this research (Loftus 1999, 61). This cost model was chosen because it requires relatively limited information and accounts for key tradeoffs involved in ship design. A key tradeoff in ship design is between size and power. In general a larger ship will have better seakeeping characteristics, but would be more expensive to build and require more power to make the required top speed. An advantage to the chosen cost model is that it considers the power required for the notional design. This cost model produces an estimate of the cost for a notional design.

These two models can be brought together within a decision support tool to aid the program office in arriving at a suitable design. The tool was programming into an Excel workbook because of the ubiquity of the software and ease of use. To quantify risk, uncertainty needed to be incorporated. Uncertainty is incorporated by using Monte Carlo simulation. The values of certain characteristics will probably change as the design matures. By entering reasonable distributions of design characteristics, many different ships could be made by randomly selecting values from these distributions. Each ship could be evaluated for seakeeping performance and cost. Repeating this process many times, large scale trends become visible. Comparing reference points such as target cost and legacy platform performance to the distribution of cost and performance outcomes reveals the probabilities of fielding an unsuitable system. These probabilities represent the risk to the program. Risk is the amount of uncertainty that exists about the suitability of the OPC for its intended use. Using this tool, a PM would be able to better influence the program outcome by adjusting the design to reduce cost and performance risk to manageable levels.

Managing risk is a way for program managers to cut through uncertainty and influence outcomes. Early in an acquisition program, a PM cannot say with certainty that a design will either fail to perform or be unaffordable. A high risk design can still result in a successful program, but the probability of that occurring is small. Providing the tool with a small amount of information, it can return a risk assessment. Using notional OPC characteristics compiled from publically available information, the tool reported that the design has a low level of performance risk, but a high level of cost risk. This risk assessment reveals that the design should change. As risk increases, the amount of effort needed to achieve a successful outcome also increases and might even become impossible. This should incentivize the PM to change course to reduce risk. A key assumption is that the requirements for the OPC are written in such a way that would allow a PM to make trades with the physical dimensions of the system. Based on a thorough understanding of how the model works, reducing the size of the OPC could trade performance for affordability. Adjusting the size of the proposed design by 15% does indeed reduce the cost risk for a modest increase in performance risk. Both risks are manageable and the reduced size model could be more likely to achieve a positive outcome. This example illustrates how the tool that was created could empower a program manager at an early point in the program to steer it toward less risky designs.

This approach achieves many of the requirements set out previously. The process is repeatable because the Coast Guard program office can use the tool. This tool is programmed into an Excel workbook, which allows the software to be transportable and useful to those that might be unfamiliar with the techniques that were used. The process is also capable of quantifying performance risk. The seakeeping performance prediction model achieves this capability by using the physical dimensions of a ship design to estimate its seakeeping performance. The process also quantifies cost risk. A cost estimating model was adopted that was used to predict the cost of notional designs. Finally, the process must be capable of validation. This research and the workbook can be reviewed by other parties to validate that what is being predicted matches with reality though the actual task of validation is outside of the scope of this research. Fulfilling these requirements means that the tool will meet the user’s needs.

While this tool meets basic requirements and is functional, it still has limitations and shortcomings that future research could remedy. One key limitation is that the seakeeping performance prediction model has not been validated. Validating this model or creating a more accurate model would require using model ship hulls and a tow tank to determine the relationships between physical ship characteristics and seakeeping performance. While this would be expensive, any future model could be implemented into this tool and would be useful for future acquisition programs. Using a physical model removes many of the assumptions made when using linear seakeeping theory and would have less uncertainty. Validating the seakeeping performance prediction model would be an important next step.

Another limitation of this approach is that this tool is predictive rather than prescriptive. Predictive models take a set of input characteristics and perform some sort of calculation to produce a predicted result. Prescriptive models take the same input characteristics, run some sort of optimization routine and deliver a presumed efficient solution within some constraints. The advantage of prescriptive models is that they can describe the best set of design characteristics, which makes them useful and desirable. A key disadvantage is that unless the constraints are perfectly well defined the solution might not be the actual best design. The user will not know until the system is completely fielded if truly the most efficient design was made. While this tool is predictive there would be value in adding a prescriptive module.

In conclusion, the offshore patrol cutter is very important to the future of the Coast Guard surface fleet. The long term consequences to the Coast Guard’s operational effectiveness and budget warrant a large amount of Congressional oversight. A key question posed by Congress is how the Coast Guard makes performance tradeoffs within the OPC design to improve affordability. This research has focused on seakeeping performance due to its criticality in performing the intended missions. A method was proposed to connect design changes to cost and performance risk within a decision support tool. This tool allows a program manager to enter a proposed design and make a risk assessment. Using the risk assessment the program manager can identify risks, examine alternatives and defend the design ultimately answering Congress’s question.

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APPENDIX. SHIPMO OUTPUT

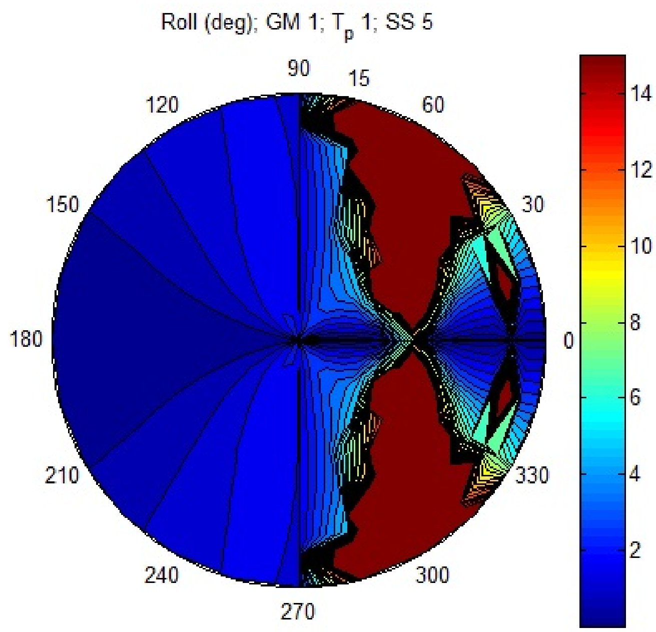

Figure 29. Roll Response

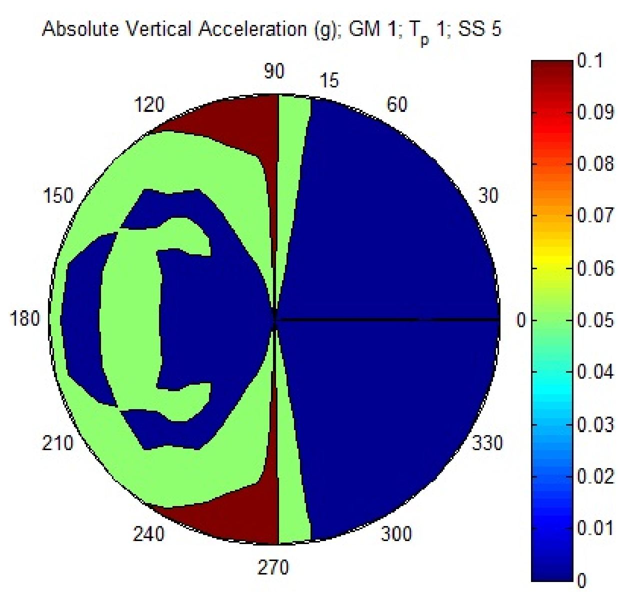

Figure 30. Vertical Acceleration Response

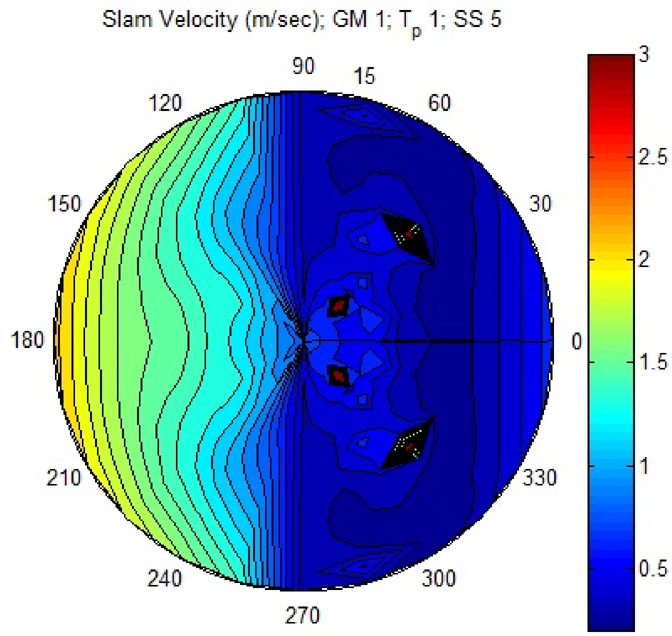

Figure 31. Slam Velocity Response

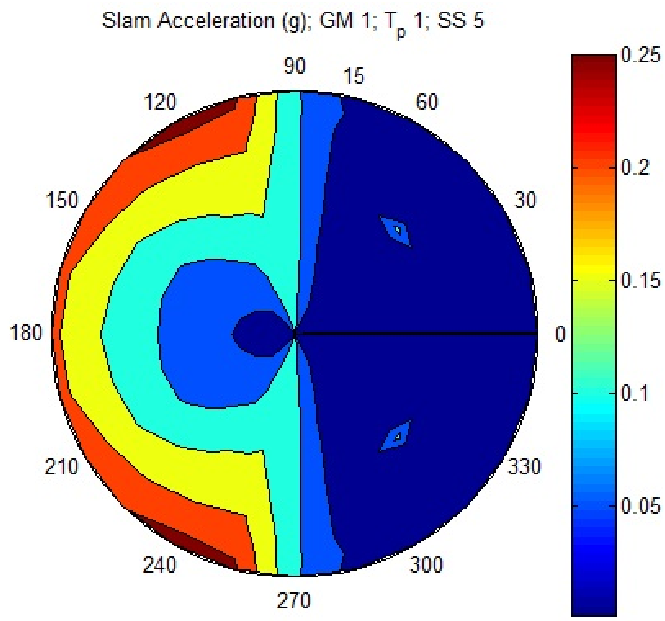

Figure 32. Slam Acceleration Response

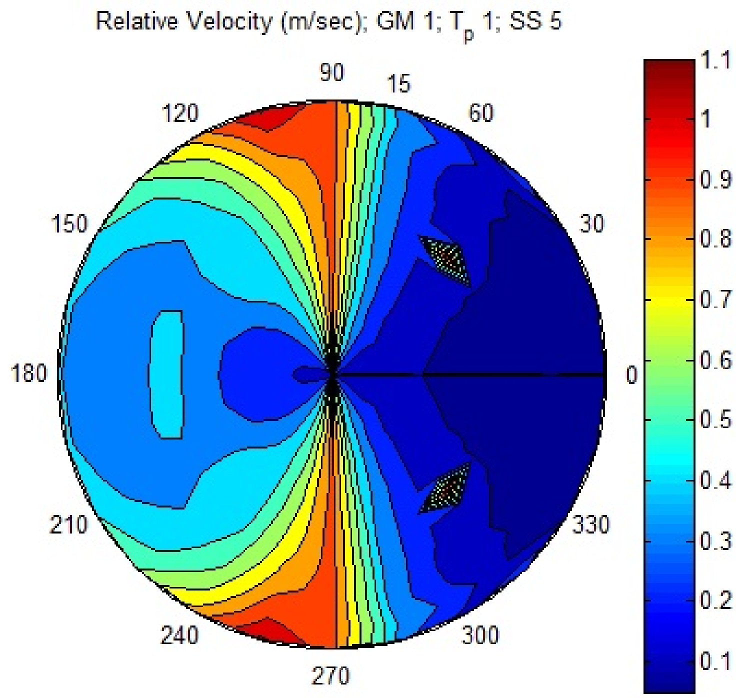

Figure 33. Relative Velocity Response

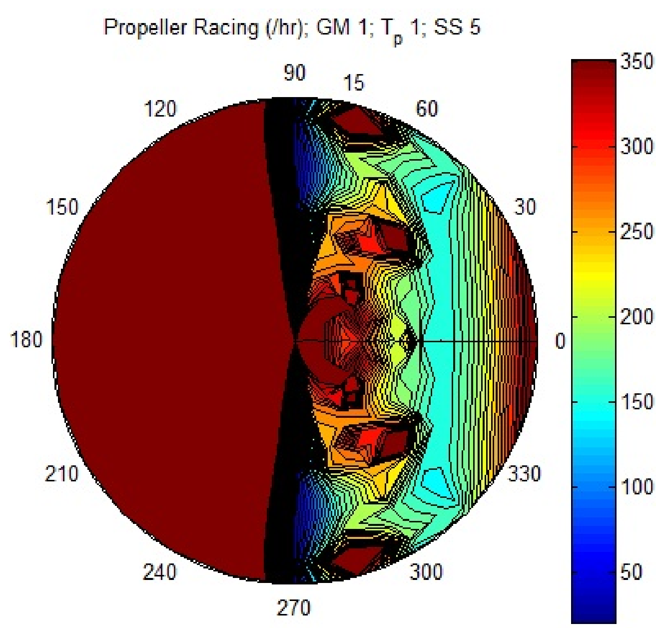

Figure 34. Propeller Racing Event Response

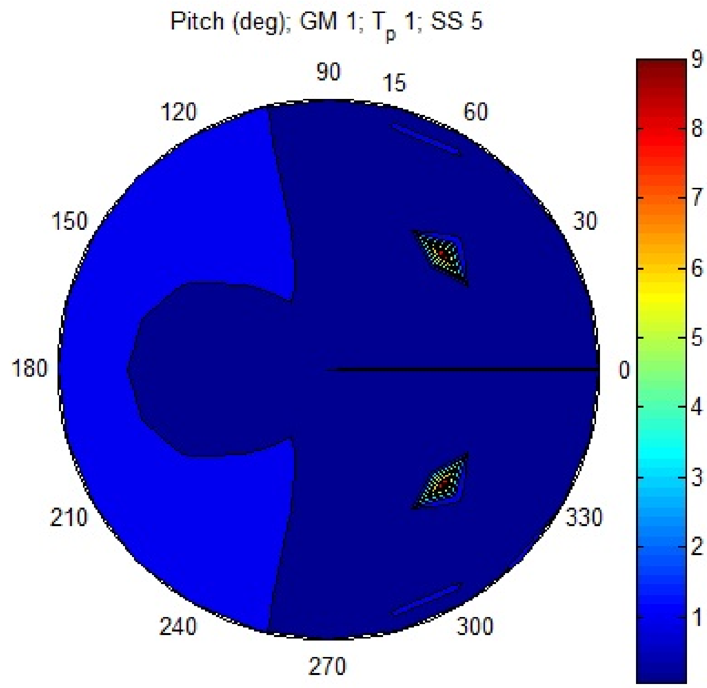

Figure 35. Pitch Response

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